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NRL Memorandum Report 1540

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INFORMATION ON OVER-THE-HORIZON RADAR
PART III

(UNCLASSIFIED TITLE)

J. R. Davis, F. M. Gager, J. M. Headrick and E. N. Zettle

with Appendices by

J. L. Ahearn, W. C. Headrick, F. H. Utley
C. B. Tesauro and E. W. Ward

U.S. NAVAL RESEARCH LABORATORY

June 18, 1964

[redacted]

U. S. NAVAL RESEARCH LABORATORY
Washington, D.C.

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CONTENT

This document contains details of equipment, equipment performance, equipment cost speculation and disposition of equipment for Over-the-Horizon radar application for CONUS protection.

AUTHORIZATION

NRL Problems 53R02-17 and 53R02-23 and
USAF MIPR (30-602) 64-3412 to the Naval
Research Laboratory dated 26 March 1964

[redacted]

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EARLY-WARNING SURVEILLANCE RADAR SYSTEMS FOR CONUS PROTECTION AGAINST AIRCRAFT, AIR-BREATHER MISSILES, AND SLBM'S (Preliminary Issue)

INTRODUCTION

PARALLEL AND OVERLAPPING EFFORT

NRL Memo Report 1422 of May, 1963, was a direct response to a DOD request for information on a MADRE type over-the-horizon radar for prototype installation on foreign soil. A follow-up joint effort by USAF and NRL to arrive at some additional cost information was made on or about 1 November 1963. Further, DOD memo of 7 February 1964 directed mainly to USAF and Navy in substance called for a study phase exercise (so called Phase I) among qualified commercial concerns on equipment costs and economic trade-offs for a state-of-the-art MADRE-like radar. Navy, as consultant to USAF's Rome Air Development Center, has prepared NRL Memo Report 1537, which is a detailed Work Statement Specification for such an OHD radar. Memo Report 1537 is in detail and should be used as the source for equipment specifications and equipment employment. Although this report addresses itself to a different mission from CONUS protection a station complement suitable for SLBM detection simply involves additional antenna complexity and a redundancy in transmitters, signal processing and data handling to satisfy the SLBM threat. It is unfortunate in the area of costing, that the efforts of the separate Air Force and Navy committees operating under DOD Memo R&E Log No. 64-1502 will not be able to digest the detailed costing of a commercial firm nature which will be one of the direct results of the aforementioned Study Phase. The commercial concern response to Phase I has a deadline of 1 September 1964. Subsequently USAF and NRL expect to digest the submitted material and report to DOD their mutual findings with recommendations. In consequence the cost information, hurriedly prepared, presented here is only of a quasi-commercial flavor, but believed to be quite realistic in the totals though discrepancies can be found.

OHD EXPERIENCE

Several years of operational experience with experimental over-the-horizon radar systems, notably the MADRE research radar, have confirmed the hypothesis that high frequency (HF) radar techniques offer a unique capability for the surveillance of large geographical areas beyond the geometrical horizon. The feasibility has been demonstrated of extending an early-warning HF radar blanket by these means at least as far as 2000 nautical miles beyond the borders of the continental United States. Indeed, it has been determined that such a radar system is capable of providing rough time-range tracking information on aircraft targets at distances from 500 to over 2000 nautical miles from the radar site and is capable as well of detecting atomic events, ICBM launches and SLBM launches of the Polaris type within this range interval as early as 50 to 70 seconds after launch and at altitudes as low as 20 kilometers. The geometry of Polaris launches between NRL and Cape Kennedy does not allow evaluation of the hostile, direct-at-radar-station launches, but it is believed that the 50-70 seconds figure is conservative and that the 50 seconds figure might be as low as 20 seconds after launch.

The attached bibliography is replete with reports on the unique features of the MADRE research type radar as well as evaluations of its capabilities against atomic events, air-breather targets, ICBM launches and SLBM launches. A resume of the unique features of the MADRE type signal processing with examples of the detection responses one can achieve with such a tool is given in Appendix A. This appendix does not cover two important additional facilities, namely target approach-recede filter separation (bibliography item 52) and the acceleration gates (bibliography item 42) both of which have been successfully evaluated and the latter is covered technically in NRL Memo Report 1537.

Numerous NRL reports have been issued on over-the-horizon aircraft detections. Appendix B is presented here as an example of extended range work. An NRL report covering a number of Polaris detections is in preparation but a short resume of activity in this area is presented, for example, in Appendix C. In addition, considerable evaluation of MADRE techniques have been made on launches of Atlas, Titan, Thor, Minuteman, etc., as the bibliography indicates, and Appendix D is an example of detection characteristics of this nature for missiles whose engines burn up to and through the ionosphere's upper layers.

It should be added that experience with existing experimental HF radar systems has shown that only the MADRE real time techniques have detected all classes of targets with distinct signatures, and that the seemingly disparate aims of detecting SLBM launches and time-range tracking of air-breather moving targets are readily satisfied with the system parameters suitable for SLBM launch detections. The reverse is not the case. A system suitable for satisfactory detection of air breathers is more economical but offers a low grade area coverage capability for the detection of SLBM launches. True, one could start with the air-breather capability with growth potential indicative of redundant additions of equipment at each station as economics and threat knowledge dictate the necessity.

In the development to follow, the particular threat toward which an HF surveillance radar is assumed to be directed is based to a large extent upon the mixed desires of the several potential users.

THE THREAT

The Russians are known to have a 350-mile and a 650-mile sub-launched ballistic missile now carried in diesel-powered submarines. It is probably correct to assume that they will acquire missiles similar to Polaris A-3 in the next five years or more. They are also believed to have cruise missiles that fly at low supersonic speeds and have a range of 350 miles when operating at 1000 to 3000 feet altitude which could be used against coastal target. This range is believed extendable to 450 miles at cruise altitudes of say 40,000 feet.

The important soft targets are SAC air bases, Interceptor bases, Command and Control Centers, and HF Radar Installations (if implemented). It would be possible, for example, for the enemy to launch cruise missiles from south of the BMEWS chain which could fly under the SAGE radars; it would also be possible for him to launch SLBM vehicles from the same region which could elude the SAGE radars (in their present configuration). With this tactic they could wipe out a large proportion of our bomber and interceptor forces before they have warning to leave the ground.

It is assumed that the proposed OTH radars will be targets which may leave them with only the main role of supplying the earliest possible warning of Soviet cruise missile and SLBM's launches. This warning is believed sufficient to save a large portion of the bomber and fighter force.

The presence of OTH radars should also force a change in the cruise missile use by loss of its value as a surprise weapon flying under line-of-sight radar coverage. Although the bomber will probably not be used in the first strike, OTH radars would provide a distant hold-back line for them and further reduce their usefulness to clean-up missions and reconnaissance.

ASSUMED OBJECTIVES

It is assumed that an HF surveillance radar system for CONUS installation is directed against a twofold threat and

(a) The detection of <u>all</u> SLBM launches within the geographical area covered by the radar is desired, and crude range and early trajectory information on these vehicles is to be provided, and

(b) The detection and tracking of all aircraft targets and air-breathers (including air-to-surface missiles and Regulus-type surface-to-surface missiles) within the geographical area covered by the radar is important.

SURVEILLANCE PROBLEM

At this point the surveillance problem begins to take on a more complicated aspect, for there are in actuality two threats against which an HF surveillance radar may be directed which will impose different requirements upon the surveillance system. If, for example, it is assumed that the SLBM threat to be met consists in part of high-performance missiles similar to the Polaris A-3, which has a range in excess of 2000 nautical miles, the HF surveillance system which promises coverage of the most remote potential launching points must have its radar sites located on the coasts. In this configuration the near-range 500-nautical-mile "skip zone," in which no coverage is provided, occurs over a potential launch area. Coastal line-of-sight radars can be constructed to fill these near-range gaps, however, and will provide early warning for SLBM vehicles. Indeed, if impact predictions and fine trajectory data are required to set up interception of the targets detected by an HF radar system, a series of surveillance and tracking coastal line-of-sight radars will be necessary or a near-in configuration of OHD radars to supplant them. In this "longest-range" configuration, the line-of-sight radars will serve the added purpose of filling gaps in the HF radar surveillance blanket with high quality detection and tracking ability where it is needed; near in OHD radars in their stead would cure the fly-under threat but provide coarser trajectory data for interception.

If, however, it is hypothesized that submarine-launched air-breathers of the Regulus type form an important part of the threat, the longest-range configuration in conjunction with line of sight radars displays a compelling insufficiency; that is, there will exist a potential launch area within the skip zone of an HF surveillance radar system from which a low-flying air-breather may be launched from a submarine, fly under the beams of the coastal line-of-sight installations and possibly evade detection entirely. To meet this threat, a system of HF surveillance radars must be constructed inland (500 nautical miles from the coast), providing coast-outward coverage but leaving the region in the range interval 1500-2000 nautical miles from the coast uncovered. In this configuration, the HF radar surveillance system will provide warning of

SLBM vehicles or air-breathers launched anywhere within 1500 nautical miles of the coast. It is this configuration in conjunction with the long-range arrangement which could provide the ultimate in coverage.

It should be emphasized, however, that an HF radar system is incapable of providing accurate trajectory information on SLBM vehicles even those whose performance is well known. Unfamiliar missiles present a serious difficulty in this realm, and it should be expected that no more than rough point-of-launch approach-recede information may be extracted with reliability from HF surveillance radar data. The upshot of this circumstance is that if near-in, fine trajectory data and impact point information are required, a complementary system of suitable coastal line-of-sight radars must be constructed. In the longest-range configuration, these line-of-sight installations could serve a double surveillance-tracking purpose, while in the coast-outward HF radar configuration they will perform the latter function alone.

In the development to follow, systems arrangement of stations are proposed which answer each of these two basic threats. The longest-range configuration is developed under the assumption that the threat toward which it is directed consists of the Polaris A-3 missile, which has a range in excess of 2000 nautical miles and utilizes rocket engines which complete their burning slightly after the missile reaches E-layer heights (100-140 km). This missile performance removes as a target signature large F-layer perturbation to which some backscatter and all forward-propagation HF surveillance systems are mainly sensitive, and requires that the enhanced reflection at low altitudes normally detected by the MADRE radar be relied upon as the primary target signature. A system which is designed to satisfy these criteria will also be able to provide detection data for longer-burning missiles which continue burning well into the upper layers of the ionosphere. The coast-outward configuration is developed to meet the same threat within its more limited range extent.

PROPOSED SYSTEM ARRANGEMENTS

Figure 1 is a map on which are drawn the extremes of coverage provided by a two-station version of the coast-outward alternative. The two radar sites are located well inland and provide 160° azimuthal coverage from the coast to a range of about 1500 nautical miles at sea. This coverage pattern is one which has been proposed by a commercial organization,* and may be seen to have an important deficiency: the North Atlantic, particularly the region presently

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* Radio Corporation of America - Defense Electronic Products proposal entitled "MOTHER An Over-The-Horizon Radar System," MO-T-790, September, 1963.

covered by the seaward extension of the DEW line, is rather inadequately covered. The apparent gaps in coverage along both coasts of the United States in Fig. 1 should not be regarded as highly significant. The inner limits of coverage in Fig. 1 were placed at a range of 750 nautical miles from the radar sites, and it is believed that these limits can be drawn in to 500 nautical miles with no difficulty. It should be pointed out that providing full coast-outward coverage with a two-station system of this type will be substantially more expensive than the system proposed by the commercial firm, however, and certain additional inadequacies exist in the commercial proposal whose elimination will raise the cost further; these points are discussed subsequently under "Data Processing."

Figure 2 is a map on which are drawn the extremes of coverage provided by a 3-station version of this same alternative. The three radar sites are located inland, as above, and provide 140° azimuthal coverage from the coast to a range of approximately 1500 nautical miles at sea. This second version provides a more thorough coverage of the North Atlantic and the entrance to Hudson Bay.

Figure 3 is a map on which is drawn the pattern of coverage provided by a system directed toward meeting the threat of long-range SLBM vehicles which might be launched as far as 2000 nautical miles at sea. This longest-range alternative involves five coastal HF radar sites, four of which provide 120° azimuthal coverage (and the fifth with a 100° azimuthal coverage) of a geographical area extending from approximately 500 nautical miles to 2000 nautical miles beyond the borders of the United States. With this alternative, an HF radar blanket is extended south from the mouth of Hudson Bay around the continental United States to the western coast of Canada. It extends in the Atlantic to the eastern shore of Iceland, the Azores, and the coast of British Guiana, and in the Pacific to the Galapagos Islands, to a short distance from the Hawaiian Archipelago, and (at its extreme northern point) to Anchorage, Alaska.

It should be stressed that all three of these alternatives have been chosen to display the differences between the approaches to the surveillance problem which they represent. The site locations and coverage azimuths represented in Figs. 1-3 should be regarded as arbitrary choices which were made solely for the purpose of demonstrating the concepts. Indeed, the parameters which are discussed below under "System Parameters" have been selected to permit the widest possible flexibility in site location and system growth, and should provide for a high degree of adaptability in the system to a broad spectrum of possible changes in the threat to be met.

A hybrid arrangement of a combination of the three station and five station proposals would obviate the use of line-of-sight radars and would be the ultimate in OTH protection.

Figures 4 and 5 are maps upon which are sketched the regions of the North American continent which would not be vulnerable to attack by long-range SLBM vehicles launched outside the nominal 2000 nautical mile range limits of the HF radar installations in the two coast-outward plans, and in the longest-range plan, respectively. It should be emphasized at the outset that the 2000 nautical mile range limit is an arbitrary choice, selected to represent the maximum range at which it is presently believed that reliable detection of SLBM launches may be made. There undoubtedly will be frequent periods in which SLBM surveillance will be effective to several hundred miles beyond this range limit; the 2000 nautical mile figure does facilitate a comparison of the two concepts, however.

All the area contained within and including the outer shaded region in Fig. 4 would be protected against undetected attack by 1500 nautical-mile SLBM's launched just outside the effective range limit of the three-station coast-outward alternative whose geographical coverage pattern appears in Fig. 2. The blacked-out area within this region would be protected against undetected attack by 2000 nautical-mile SLBM's launched from the same ranges.

The inner shaded region in Fig. 4, which includes most of the completely blacked out area, would be protected against undetected attack by 1500 nautical-mile SLBM's launched just outside the effective range limit of the two-station coast-outward alternative whose coverage pattern appears in Fig. 1. No region is protected against undetected attack by 2000 nautical-mile SLBM's under this alternative. It should be noted that large areas of the Pacific northwest, the whole Pacific coast region, all of Florida and most of Maine are left unprotected against undetected attack by 1500 nautical-mile missiles under even the three-station coast-outward alternative.

All the area continued within and including the outer shaded region in Fig. 5 would be protected against undetected attack by 1500 nautical-mile SLBM's launched just outside the effective range limit of the five-station longest-range configuration whose coverage pattern appears in Fig. 3. The inner shaded region would be protected against undetected attack by 2000 nautical-mile SLBM's launched from the same regions. It should be noted that the increased protection afforded by this alternative completely removes the threat of undetected attack by 1500 nautical-mile missiles to the California coast and Florida, and in addition greatly expands the region in which undetected attack by 2000 nautical-mile SLBM's is not possible. Protection of the Pacific Northwest is not improved, however.

THE AREA COVERAGE PROBLEM

Reliable coverage with an HF radar system of a range interval extending from 500 to 2000 nautical miles will normally require that this interval be broken up into three nominal 500-nautical-mile segments and each segment illuminated with a separate frequency. The variety of propagation conditions which govern the transmission of HF radiation over an ionospheric path will permit reliable coverage of the 750-1750 nautical-mile portion of this interval, and less reliable coverage of the 500-750 and 1750-2000 nautical-mile extremes of the range interval with only two separate frequencies. Figures 6 and 7 are drawings of the geographical coverage provided in a 10° (assumed antenna azimuth interval) sector by the three-frequency and two-frequency alternatives, respectively. In Fig. 6 the range interval is divided into three equal segments, and each segment is labelled to indicate that a different frequency should be used to illuminate it. In Fig. 7 the 750-1750 nautical-mile interval is divided similarly, and the 500-750 and 1750-2000 nautical mile range extremes are shaded to indicate that coverage in these regions is reduced in reliability under the two-frequency alternative.

Ionospheric conditions will require that discrete frequencies in a band extending from (say) 5 to 28 Mc/s be available for use by the HF radar surveillance system. Single-hop F_2-layer propagation normally will be utilized, and Fig. 8 is a cross-sectional view of a typical two-frequency single hop coverage pattern over the 750-1750 nautical mile range interval. An ionospheric virtual height of 300 km has been chosen to represent normal daytime propagation conditions. The lines at 20 km and 136 km have been drawn in to represent the range of altitudes over which a Polaris A-3 missile is conservatively expected to be visible to an HF radar system. The lower limit of 20 km has been selected to allow for the initial low-velocity portion of the vehicle's flight, extending over the first 50 seconds or so, and the upper limit of 136 km (through which a Polaris passes at approximately 120 seconds after launch) has been selected as a representative burnout altitude; it is at burnout that an HF radar normally loses an SLBM echo. The coverage provided between these limits by one frequency is shaded, and that provided by the second frequency is dotted. The alternative three-frequency case involves no more than the addition of a third coverage interval and alteration of the range limits.

It will at times be necessary to make use of different modes of propagation than the simple single-hop F_2-layer mode, however. At times (such as winter nights) when the F_2-layer is particularly low, it will be possible to illuminate the farthest extreme of the

500-2000 nautical mile range interval only by utilizing a two-hop F-layer propagation mode. Figure 9 is a cross-sectional view of the coverage provided by simultaneous use of a single-hop mode and a two-hop mode on an occasion when the ionospheric virtual height has decreased to 225 km. The two-hop mode (shaded) is used to cover the 1500-2000 nautical mile segment (on the second hop) as well as the 500-1000 nautical mile segment (on the first hop), and a separate single-hop made (dotted) on a different frequency, is used to cover the 1000-1500 nautical mile interval. It will not be possible under ordinary conditions, of course, to rely on this two-frequency technique to cover reliably the full 500-2000 nautical mile range interval. Two coverage patterns were used in Fig. 7 merely to simplify the illustration.

It will also at times (such as summer mid-day periods) be desirable to make use of E-layer refraction to illuminate the 500-1000 nautical mile range interval, because E-layer blanketing may prohibit the use of F-layer propagation during these periods at the low frequencies, and high angles of radiation, which will be necessary to cover this near interval.

It need hardly be mentioned that a means <u>must</u> be provided the operators to select appropriate frequencies for thorough geographical coverage. A step- or sweep-frequency vertical sounder and oblique sounding means should be installed at each radar site for this purpose as recommended in NRL Memo Report 1537, and soundings should be made routinely as a basis for detecting short-term changes in ionospheric conditions which will affect the choice of operating frequencies.

SYSTEM PARAMETERS

In order to insure that the highest possible degree of flexibility is built into the HF surveillance radar system, a modular concept of construction is envisioned. Component parameters have been selected from the details in Memo Report 1537 and some of these are discussed below:

(1) <u>Antenna</u>:

The antenna, which will be used with a duplexer for both transmitting and receiving, will consist of an array of wideband, high-directivity elements. It is proposed that each antenna installation be split horizontally into individual 10° sectors, each of which can be covered by an antenna module of approximately 25 db directivity. At lease one antenna design permits the modular concept so that azimuthal coverage by an installation may be expanded simply through the addition of elements to the existing array. The antenna should be usable over a frequency band extending from (say) 5 to 28 Mc/s without tuning. Table 1 contains a list of the radiation takeoff angles which will be necessary to cover the 500-2000 nautical mile range interval under a variety of ionospheric conditions. It should be noted that 2-hop propagation will be necessary to cover the far extreme of the range interval under conditions in which the F-layer virtual height is in the 200-250 km altitude region. Takeoff angles from 1° to 30° will be adequate to provide coverage over the full range interval during most periods. Under conditions in which the F-layer virtual height is in excess of 300 km, however, higher takeoff angles will be necessary to cover the 500-750 nautical mile portion of the range interval by F-layer propagation. This condition normally occurs during periods in which an E-layer is available, however, and it may be seen from Table 1 that in this situation takeoff angles of 5° to 10° will be adequate to cover the near portion of the range interval. Figure 10 is a diagram of a vertical pattern which will satisfy the takeoff angle requirements for the HF surveillance radar antenna. The solid lines define the lobe structure necessary to cover the 1° to 30° span of takeoff angles, and correspond to antenna elements which should be usable over the full 5 to 28 Mc/s frequency range. The dashed lobe is one which could be constructed to provide high takeoff angle radiation if near range F-layer coverage is desired during periods in which the F-layer virtual height exceeds 300 km. The elements which form this lobe need only be usable in say the 5 Mc/s to 10 Mc/s band.

(2) Power Sources:

The use of high average power excitation is mandatory for detecting the launch phase of SLBM vehicles and for tracking remote aircraft or air-breather targets, and it is envisioned that power source modules be designed to produce 200 kw of average power and 10 Mw of peak power on each active 10° beam. These power sources should be broad-banded to allow for frequent rapid variations in transmitted frequency throughout the 5 to 28 Mc/s system band. It is proposed that under normal operating conditions two 100 kw or four 50 kw power source modules will be utilized simultaneously to transmit energy into a given geographic area, and that a scanning technique will be exploited to minimize the total number of power sources necessary to provide complete coverage.

(3) Data Processing:

The HF surveillance radar should make use of the coherent MTI techniques which have been proven in the MADRE experimental HF radar facility, as discussed in Appendix A. It has been found during several years of operation of the MADRE radar that a minimum time-on-target, or dwell time, of three seconds is necessary to obtain a reliable aircraft return or missile signature. This three second dwell period is strongly recommended as a primary design criterion, although substantial flexibility in the data processing system and antenna scanning system are planned to meet varying conditions. It is proposed that adequate flexibility be built into the HF surveillance system to permit operation with dwell periods extending from less than 1 to 20 seconds as detailed in NRL Memo Reports 1422 and 1537.

A second criterion which has been extracted from operation of the MADRE radar is that of total scan time. It has been found that Polaris A-3 missiles, which burn out approximately 120 seconds after launch, are visible to an HF radar for a period of 20 to 60 seconds. Positive identification of such a missile absolutely requires that at least two three-second observations be made within this period, and hence it is proposed that the total scan time should not exceed about ten seconds. In this realm as well, a high degree of flexibility should be built into the system to permit operation over a wide band of scan periods, allowing full-time dwelling upon selected geographical areas and simultaneous long-scan (20 to 30 seconds) coverage of other regions. These details are found in NRL Memo Reports 1422 and 1537.

It should be mentioned that the commercial two-station plan, which was touched on previously under "Proposed Systems," does not provide a long enough dwell period or short enough total scan time to satisfy the criteria outlined in this section for both air breathers and missile targets.

IMPLEMENTATION AND OPERATION

Table 2 contains a brief list of the primary requirements for complete HF radar surveillance systems designed for maximum protection against the two threats discussed above. In each case, the antennas are divided into 10° sectors, three frequencies are utilized to provide coverage in the full 500-2000 nautical mile range interval, and a nine second total scan time and three second dwell time are exploited to achieve a high probability of detection. Most items on the list are discussed in greater detail in NRL Memo Reports 1422 and 1537. Item nine consists of an estimate of the range and azimuth resolution with which aircraft targets may be located with the HF radar surveillance system.

There are several alternative solutions to the surveillance problem, all of which result in varying degrees of degradation in system performance. One of these alternatives has been discussed briefly under

"The Area Coverage Problem," and involves the use of two rather than three frequencies on each antenna sector. This option provides thorough coverage over any 1000 nautical mile section within the 500-2000 nautical mile range interval, and can provide somewhat incomplete coverage of the remaining 500 nautical mile section. This option results in a reduction by one-third in the number of power sources required, or (alternatively) permits a six second total scan time to be used instead of the nine second scan time which has been proposed above. A second alternative involves retaining the three frequency coverage feature, but reducing the number of power sources and extending the total scan period. This option would be workable in a situation in which aircraft (or cruise missile) tracking is a major consideration, for such relatively slow, constant velocity targets require less frequent observations. It should be emphasized, however, that performance of the surveillance system under this option would not be adequate to provide reliable warning against SLBM launches.

It is possible under the modular design concept to plan for installation of the HF radar surveillance system over an extended period of time and yet satisfy some of the surveillance requirements continuously. It would be possible, for example, to construct the antenna and housing for (say) a station placed to cover the North Atlantic, and to install <u>some</u> of the power sources and associated data processing equipment at the outset. This station could then be used effectively to track aircraft and air breathers, and would be useful if cruise missiles are considered to be the most important initial threat. Indeed, this single station could in all likelihood take over the area assignment of the North Atlantic barrier and FAA requirements, and could be expanded at a later time to protect the United States against the increased threat of Polaris A-3 type SLBM vehicles. A similar gradual expansion technique might be employed in construction of the North Pacific station, and would probably be useful in construction of the Caribbean station (which could be used, initially, to monitor air traffic in the vicinity of Cuba).

THE FREQUENCY ASSIGNMENT PROBLEM

The feasibility of extended range radar, obtained by using the ionosphere for refraction, has been well demonstrated and a new tool is available. The potential utility of a number of such radars is evident. One of the problems is that the HF portion of the frequency spectrum need be used, and this portion is heavily occupied at present by legitimate use mixed with antiquated practices. An HF radar designed to detect targets in the hundreds of square meters size at 2000 nautical miles is a high powered sophisticated device, and if an appreciable portion of the world is to be under surveillance a number of radars are required. Indiscriminate or random frequency operation of a large group of such radars is not always compatible for such radars or present HF occupancy and usage. Therefore, it is proposed that all HF radars share the same channel assignments. Using this procedure simultaneous selection of the same channel or channels by more than one station will occur. With coherent pulse doppler systems employing backscatter rejection filters coincident operation on the same frequency by a number of radars is possible. The transmitted signals from one radar station that constitute interference when received at another station can be combed out by the backscatter rejection notches in the signal processor. The requirements for achieving this are that frequency assignments be closely adhered to, say within one cycle per second and that repetition rates be likewise nearly the same. That is, each station independently chooses the frequency and repetition rate required, but from the designated sets of frequencies and rates. This capability of a number of coherent MTI radars to "live together" renders the concept of a CONUS network practical.

The HF radar system needs frequencies spaced throughout its operating range. A channel bandwidth of at least 6 kc is desirable and will be specified. It is suggested that in the frequency range of 5-28 Mc, three U.S. government channels per megacycle be made available at the low frequency end tapering to one channel per megacycle at the high end. These channels will not all be occupied simultaneously and need not be clear; however, it is desirable that the HF radar have some priority.

An aside is in order here. The NRL-MADRE research radar has been operated, for the most part, on Washington area naval transmitting frequencies. This work has been on a non-interference basis with no priority to NRL and has been surprisingly successful. Complaints have been negligible except for times when a 60 kc spread frequency technique (sideband pair stepping) has been employed.

The proposed primary frequency assignment system will be restated. Channels of 6 kc bandwidth should be designated available for HF radar. The channel spacing between 5 to 28 Mc should be in 5% steps as nearly as possible, and presumably these channels will be in the existing United States military assignments. Preparations should be made to permit frequency agile operation on any clear channel in the event that some emergency requires such operation. This frequency agility feature is detailed technically in NRL Memo Reports 1422 and 1537.

COUNTERMEASURES CONSIDERATIONS

The vulnerabilities of HF radar systems to countermeasures are not unique because the radar art has never produced a radar incapable of being jammed if the adversary chose to make the effort. Like all radars, HF radars are susceptible to near range jamming in the ground wave range and airborne jamming in the line of site range particularly. In the vast area of illumination, small jammers located in the sectors of coverage could be effective, but such a program is a vast undertaking. This forces the opponent to use more power and jam through the side lobes. This is discussed in NRL Memo Report 1422.

The prudent use of the techniques of design to provide high dynamic range and a method of transmission-frequency agility to be used at moments of diplomatic tension or in war time is set forth in NRL Memo Reports 1422 and 1537. The technical details of accomplishing some of these advances are shown in NRL Memo Report 1537.

SLBM and airbreather detection efficiency is best served by a minimum of three seconds time on the illuminated area and return thereto in six to 10 seconds. The three second figure could be reduced to two or even one second with the flexibility in equipment called for in the two referenced NRL Memo Reports. It is pointed out that one second look time degrades the system performance and is recommended only in case of necessity.

Reference is made to the <u>Research and Development Status Section</u> of this report where activity is under way to perfect the high dynamic range signal processor and the frequency agility feature, both to be evaluated in the NRL MADRE research radar. There is also reference to a 100 db dynamic range processor and an optical processor in the proposed research under this section.

It is thus believed that the tools at hand and those in process will provide a means of operation free from manual jamming techniques and some automatic means.

It should be pointed out that any proposed HF radar is indeed a potential jammer of no small capability and that this facility may be militarily useful at times.

OPERATING TIME CONSIDERATIONS

The rising and setting sun make cyclical changes in the ionization content of the ionosphere. This stimulus and the known slow decay phenomena associated with its absence are quite well understood and give rise to the specification features in NRL Memo Report 1537 for vertical and oblique sounding techniques to assist the operator in selecting correct frequencies and arriving at true ground range from radar ranges.

Ionosphere disturbances which violently alter the ionosphere and the sometimes attending aurora to affect ionosphere use as the HF communicators are well aware. NRL Memo Report 1422 treats the estimated available operating time one might expect in quite some detail, and as a round figure one might expect a random distribution of this effect, not associated with weather, so as to conservatively provide a figure from 70 to 90 percent effectiveness over a wide north latitude distribution.

OHD RADAR BLIND SPEED

The key features, which made OHD radar a practical device were the determination of the spectrum of normal backscatter and the development of the means to eliminate these spectrum components. The process of eliminating the backscatter components sets a minimum doppler speed which can be detected, say 75 to 100 knots, and this states that the OHD radar will be blind to opening and closing speeds of moving targets in this speed range. It is immediately apparent that ships of all classes will be eliminated in the comb filtering process. It is also obvious that the air breathers with low opening and closing speeds will not be detected. It should be stated that SLBM launches produce spread-spectrum responses which will spill over the comb filters and produce the normal desired response and thus those targets are not particularly limited.

There is an investigation underway at NRL on the use of quiescent listening stations remote from the radar in a quasi bistatic mode to overcome to a degree the blind speed cones of silence for air breathers. This subject is treated in NRL Memo Report 1422 and NRL is obligated to produce a more extensive report on this study for RADC and DOD by 1 September 1964.

SITE CONSIDERATIONS

UTILITIES - The costs presented subsequently do not include water systems, sewage and waste disposal systems or electrical power sources other than a relatively small emergency unit. In consequence one could save initial costs and maintenance upkeep if the chosen sites were in near proximity to a trunk sewer, power lines, or natural gas pipe lines.

The electrical load presented by the station is a function of the number of transmitter-receiver complexes. The material to be presented indicates that the load centers produced by these stations for a commercial power company or some local diesel or gas turbine station is not a negligible item. It is estimated that a station with but one wide band transmitter-receiver complex of 200 kw average power (10 Mw peak) would produce a KVA load to the load center of about 1630 KVA. When one notes that some stations may have a maximum of 16, 14, 12, 10, or 8 transmitter-receiver complexes depending on the choice involved, the corresponding KVA demand presented to the load centers would be 26,000 KVA, 22,800 KVA, 19,500 KVA, 16,300 KVA, and 13,000 KVA. The generator capacity today and even that of the available gas turbine driven peak-load substations dwarf these demands, but they are substantial when one considers that many small towns present much less load.

LAND REQUIREMENTS - The estimated land requirements for the type stations herein considered run from three to five square miles in substantially square form. The land should be relatively flat and offer no special obstructions to a 20-30 mile distant horizon which should be preferably less than 2 degrees elevation.

GOVERNMENT PROPERTY - There are located throughout the United States camps, training centers, airfields, and emergency air strips which are closed or on low grade, stand-by status. Many of these have both water and waste systems which could be reactivated. In addition, some form of electrical load center was established with a power company where these facilities were built. In some cases these electrical load centers will be adequate. Thus, since the exact location of a station is not inflexible, the location of government owned establishments should be studied and their use contemplated to reduce initial costs.

COST CONSIDERATIONS

It was deemed important to estimate the installed costs of equipment, but more important to estimate on a ten year life the accumulated cost so that these could be compared with some present commitments which would be superfluous in some cases, if OHD radars were installed for CONUS protection.

PRESENT COMMITMENTS - The present commitments, such as flight extensions of the DEW line with their attendant ships, ship bases, airfields, air bases, crew complements, and special electronic equipment constitute an effort which is but a small segment of the whole CONUS problem. There is also the problem of the net of shore based radars which are now being considered for upgrading so as to be effective on both airbreathers and missiles. If these exist in sufficient numbers, their upgrading may be advantageous as noted previously in the speculations on combined line of sight and OHD radars, even with the fly-under, fly-over deficiency.

One should think of the initial cost and yearly upkeep of the BMEWS radar sites, their limited coverage and the fly-under threat to them. OHD radars could be a tremendous addition to their data. One should not be under any illusions as to the system costs of OHD radars when complete protection for CONUS is envisioned.

There is thought also that the present flight extensions of the DEW line might be increased and extended for full CONUS protection. If one passes up the cost of the new additional electronic equipment and the cost of the additional ships and planes, with their necessary bases and crews, and just looks at the cost of the present flight extensions, which only supply a small portion of the problem solution, it will be found that the bare minimum is about 125 millions a year or 1.25 billions on a ten-year basis. Others may wish to add to this last figure the cost of the ships, aircraft, crews, bases, etc., amortized over a ten year period, to keep this function a going concern. If one conservatively guesses that the yearly addition is another 125 million or so then the true cost is more nearly 250 millions a year or 2.5 billions over a ten-year period to just keep in business on the partial job. The authors do not know the penetration efficiency now provided by the present flight extensions of the DEW line with the attending picket ships, communications problems, etc. No doubt, penetration exercises have been performed and those with this knowledge are aware of whether or not the present flight and picket ship density is sufficient, or should be upgraded, to equal that which one could rightly expect from an OHD radar. If the density should be increased for comparison purposes, then the cost mounts also.

If indeed the nearly true cost for a ten year period is in the neighborhood of 2.5 billion dollars, one could take the arc of extension now provided by flights and possibly pro rate the cost to complete the circle. Perhaps this has already been accomplished by others but for our purposes here let it be said that the result must be staggering. Thus, the costs of the proposed systems over a ten year life should be weighed against the present cost commitments with the realization that full coverage for CONUS is envisioned with OHD radars.

This report shows that a growth in threat from airbreathers to a combination of airbreathers and SLBMs has a corresponding growth potential at each station as well as the addition of stations above two to complete the circle of coverage.

Although the authors with their limited knowledge could arrive at their preferred plan, which in their judgment would be the most effective, it is realized that they do not have at their command all prevailing knowledge necessary for such a decision. Thus the various planned arrangements of stations, with their stated advantages and disadvantages, have been set forth, with costings, so that those more capable of making the selection will have a modular form before them which they can piece and fit to the actual circumstances.

[redacted]

COSTING BASE

The following program of costing is based upon the previously enumerated station location plans. The costs set forth include:

(a) Installation in readiness for operation
(b) Land preparation
(c) Sewer and water lines to a nearby assumed facility
(d) Power lines to nearby assumed utility system
(e) Emergency power source for 300 kw operation
(f) Buildings
(g) Operation in a frequency range 5 to 28 Mc
(h) Maintenance and operation

but do not include:

(a) Land acquisition costs (see comments on government land)
(b) Communications facilities to data-use centers
(c) Inevitable increases in costs due to delays in executing a procurement program
(d) Utilities facilities (if required) and
(e) Utilities consumption costs.

The cost*material about to be presented is hurriedly prepared and some discrepancies are readily noted. It is broken down by azimuth coverage two ranges (750-1750 NM) and (500-2000 NM) and minimum costs and maximum costs are designated for each range for both the initial cost of equipment and the ten year life cost. The term minimum cost is used for a facility suitable for airbreather detection but low grade for SLBM detection. The maximum figure is for a detection facility suitable for SLBM and all airbreathers. The significance of the various costs as they relate to range and time-on an illuminated area and time-off this same area is detailed under the previously treated section "Data Processing."

* Decimals figures not significant - preserved for reference to work sheets only.

[redacted]

COSTS OF STATION ARRANGEMENTS

2 STATIONS 160° AZIMUTH - Consider the proposed two station configuration with 160° azimuth per station with two range situations.

750-1750 NM RANGE (Two Frequency Operation)

		INITIAL COST	10 YR COST	SEC. TIME ON-OFF
min-1	$4\frac{(T-R)^s}{Sta}$	94.6 M	124.6 M	(3-21)
max-a	$8\frac{(T-R)^s}{Sta}$	150.6 M	190.6 M	(3-9)
max-b	$16\frac{(T-R)^s}{Sta}$	262.6 M	302.6 M	(3-3)

These costs would run from about 95 M for the minimum station combination to 150 M to 263 M depending upon the choice of on-off time of (3-9) or (3-3) seconds, with the ten year cost ranging from about 191 M to 303 M depending upon the growth rate chosen.

500-2000 NM RANGE (Three Frequency Operation)

		INITIAL COST	10 YR COST	SEC. TIME ON-OFF
min-1	$4\frac{(T-R)^s}{Sta}$	94.6 M	124.6 M	(3-33)
max-b	$16\frac{(T-R)^s}{Sta}$	262.6 M	302.6 M	(3-6)

These costs would run from about 95 M for the minimum station combination with on-off time of (3-33) seconds to about 263 M for a (3-6) second on-off time. The ten year cost would run for the minimum about 125 M to about 303 M depending on the choice and growth rate chosen.

3 STATIONS - 140^{o} AZIMUTH - Consider the proposed three station configuration with 140^{o} azimuth coverage per station with two range situations.

750-1750 NM RANGE (Two Frequency Operation)

	INITIAL COST	10 YR COST	SEC. TIME-OFF
min-1 $2\ \frac{(T-R)^s}{Sta}$	80 M	125 M	(3-39)
min-2 $4\ \frac{(T-R)^s}{Sta}$	122 M	167 M	(3-18)
max-a $7\ \frac{(T-R)^s}{Sta}$	185 M	245 M	(3-9)
max-b $14\ \frac{(T-R)^s}{Sta}$	331 M	391 M	(3-3)

In this arrangement one has several choices. The minimum of 80 M to 122 M for an on-off ranging from (3-39) to (3-18) coupled with a maximum condition of 185 M to 331 M depending on the choice of on-off times of (3-9) or (3-3) seconds. The ten year cost ranges from (125-167) M to (245-391) M depending upon the combination and growth rate chosen.

500-2000 NM RANGE (Three Frequency Operation)

	INITIAL COST	10 YR COST	SEC. TIME-OFF
min $3\ \frac{(T-R)^s}{Sta}$	101 M	146 M	(3-39)
max $14\ \frac{(T-R)^s}{Sta}$	331 M	391 M	(3-6)

In this arrangement the minimum of 101 M provides an on-off time of (3-39) seconds while the maximum of 331 M provides corresponding times of (3-6) seconds. The ten year cost ranges from 146 to 391 M depending upon the growth rate chosen.

5 STATIONS - (4-120° AND ONE 100° AZIMUTH)- Consider the proposed five station combination of four 120° azimuth stations plus one 100° azimuth station, with two range situations.

750-1750 NM RANGE (Two Frequency Beam Operation)

		INITIAL COST	10 YR COST	SEC. TIME ON-OFF
120°	min $2\frac{(T\text{-}R)^s}{Sta}$	93.9 M	153.9 M	(3-33)
120°	max $8\frac{(T\text{-}R)^s}{Sta}$	261.9 M	341.9 M	(3-6)
100°	min $2\frac{(T\text{-}R)^s}{Sta}$	28.9 M	43.9 M	(3-27)
100°	max $10\frac{(T\text{-}R)^s}{Sta}$	72.8 M	92.8 M	(3-3)
100°	max $5\frac{(T\text{-}R)^s}{Sta}$	49.9 M	69.9 M	(3-15) not recommended

500-2000 NM RANGE (Three Frequency Beam Operation)

		INITIAL COST	10 YR COST	SEC. TIME ON-OFF
120°	min $4\frac{(T\text{-}R)^s}{Sta}$	149.9 M	209.9 M	(3-24)
120°	max $12\frac{(T\text{-}R)^s}{Sta}$	373.9 M	453.9 M	(3-6)
100°	min $3\frac{(T\text{-}R)^s}{Sta}$	35.9 M	55.9 M	(3-27)
100°	max $10\frac{(T\text{-}R)^s}{Sta}$	72.8 M	92.8 M	(3-6)

In the 750-1750 NM situation the minimum station combination has an initial cost of 123 M and a ten year cost of 198 M to a maximum station combination cost of 334 M, with a corresponding ten year cost of about 435 M. The on-off times of a mixture of (3-33) and (3-27) are for the minimum case and a (3-6) and (3-3) mixture for the maximum case.

In the 500-2000 NM situation the minimum station combination has a mixture of on-off times of (3-24) and (3-27) seconds with a corresponding cost of about 186 M and a ten year cost of about 266 M. The maximum station combination has an initial cost, for on-off times of (3-6) seconds, of 446 M with a corresponding ten year cost of about 546 M.

ALTERNATIVE 5-STATION ARRANGEMENT

(4-120° Azimuth Stations and 1-80° Azimuth Station)

Consider an alternative of the five station arrangement of a combination of four-120° azimuth stations and one 80° azimuth station, with two range situations.

750-1750 NM RANGE (Two Frequency Beam Operation)

			INITIAL COST	10 YR COST	SEC. TIME ON-OFF
120°	min	$2\frac{(T\text{-}R)^s}{Sta}$	93.9 M	153.9 M	(3-33)
	max	$8\frac{(T\text{-}R)^s}{Sta}$	261.9 M	341.9 M	(3-6)
80°	min	$2\frac{(T\text{-}R)^s}{Sta}$	19.1 M	34.1 M	(3-21)
	max	$4\frac{(T\text{-}R)^s}{Sta}$	33.1 M	48.1 M	(3-9)

500-2000 NM RANGE (Three Frequency Beam Operation)

			INITIAL COST	10 YR COST	SEC. TIME ON-OFF
120°	min	$4\frac{(T\text{-}R)^s}{Sta}$	149.9 M	209.9 M	(3-24)
	max	$12\frac{(T\text{-}R)^s}{Sta}$	373.9 M	453.9 M	(3-6)
80°	min	$2\frac{(T\text{-}R)^s}{Sta}$	19.1 M	34.1 M	(3-33)
	max	$8\frac{(T\text{-}R)^s}{Sta}$	61.1 M	81.1 M	(3-6)

For the alternative situation in the 750-1750 NM range, the minimum station combination has an initial cost of about 113 M and a ten year cost of about 188 M, to a maximum station combination initial cost of about 294 M, with a corresponding ten year cost of about 390 M. The on-off times of a mixture of (3-33) and (3-21) are for the minimum case and (3-6) and (3-9) for the maximum case.

For the alternative situation in the 500-2000 NM range, the minimum station combination has an initial cost of about 169 M and a ten year cost of about 244 M, to a maximum station combination cost of about 435 M, with corresponding ten year cost of 535 M. The on-off times of a mixture of (3-24) and (3-33) are for the minimum case and (3-6) for the maximum case.

RESEARCH AND DEVELOPMENT STATUS

RESEARCH IN PROGRESS

(a) Development of frequency agile techniques compatible with matched filter signal processing.

(b) Investigation of very broadband high-gain steerable antenna arrays.

(c) Development of extended dynamic range (60 db or better) signal processors.

(d) Investigation of 100-db dynamic range, electrostatic storage signal processor.

(e) Development of matched acceleration filters.

(f) Investigation of target analysis and presentation techniques.

(g) Studies aimed at definition of the HF propagation medium based upon vertical and oblique soundings.

PROPOSED NEW RESEARCH

(a) Continue and emphasize studies of the propagation medium

(b) Investigate known techniques for long pulse transmission and processor compression - compatible with the HF spectrum.

(c) Study application of optical matched filters to electronically stored signals.

(d) Study applications of digital techniques aimed at further extension of signal processor dynamic range and flexibility.

ACKNOWLEDGMENT

The authors express their appreciation to Dr. R.C. Guthrie, Superintendent of the Radar Division, Mr. I.H. Page, Consultant to the Radar Division and Dr. C.E. Cleeton, Associate Director of Research for Electronics all of the Naval Research Laboratory for their comments. The authors also express appreciation for the efforts of Messrs. D. Rohlfs, G.A. Skaggs, F.E. Boyd, G.A. Morgan, J.F. Thomason, and J.M. Hudnall for their work in making the data of the appendices possible. Mrs. M.G. Martin and Mrs. M.L. Etzel are also commended for proof, typing, and form suggestions.

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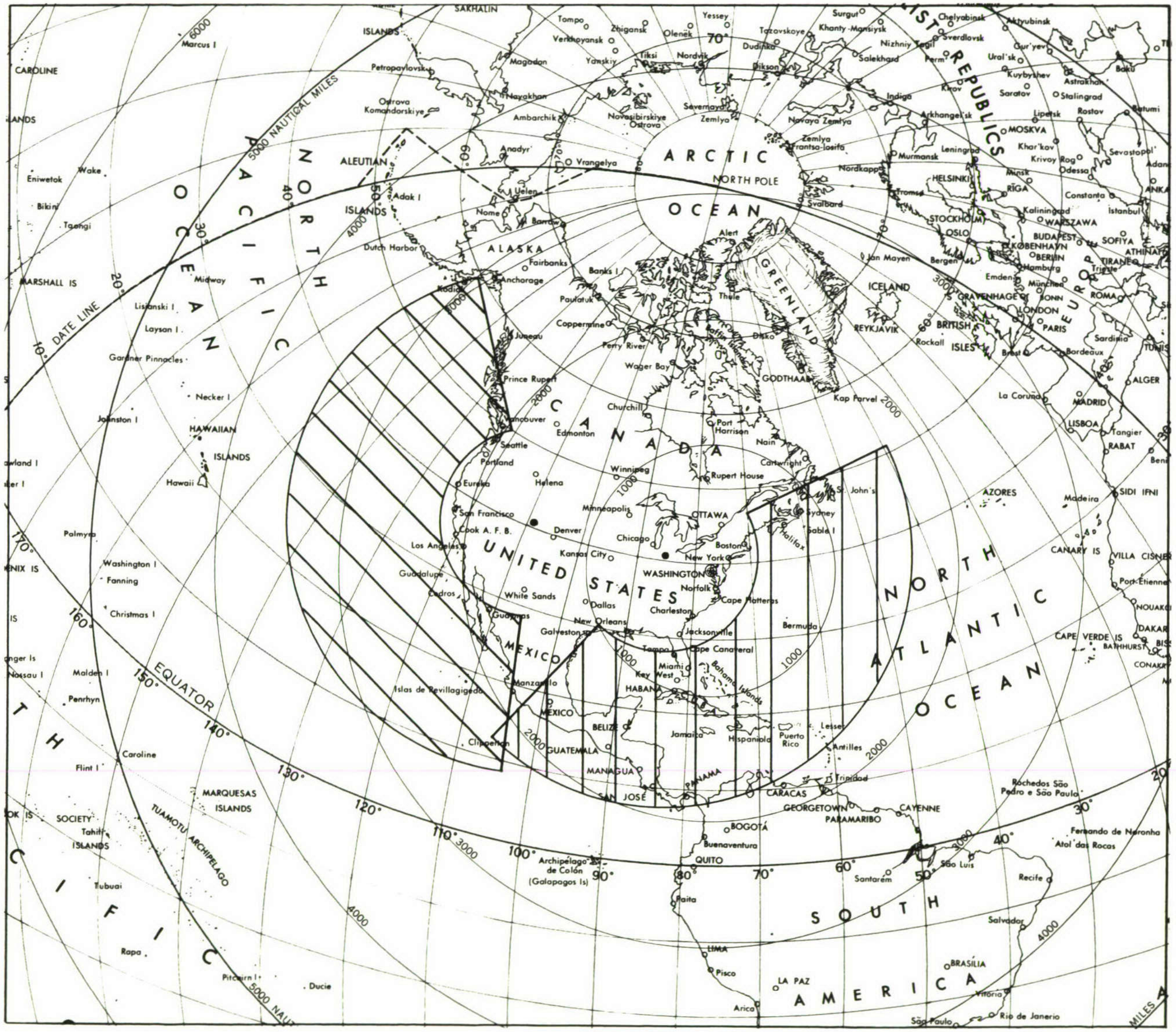

Figure 1 - Geographical coverage pattern provided by two-station HF radar surveillance system proposed by commercial firm for "Coast-Outward" coverage.

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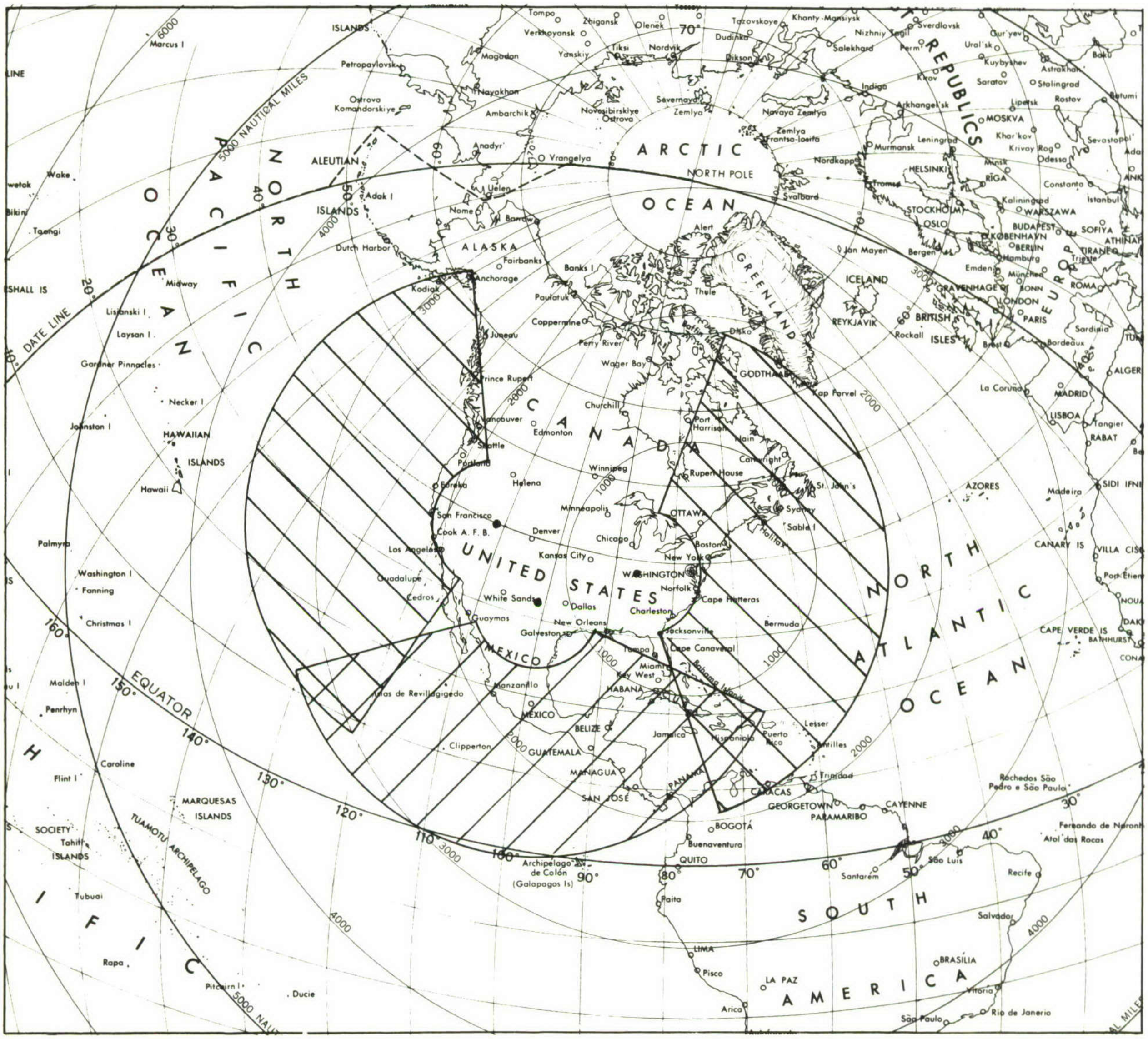

Figure 2 - Geographic coverage pattern provided by three-station version of HF radar surveillance system designed for "Coast-Outward" surveillance.

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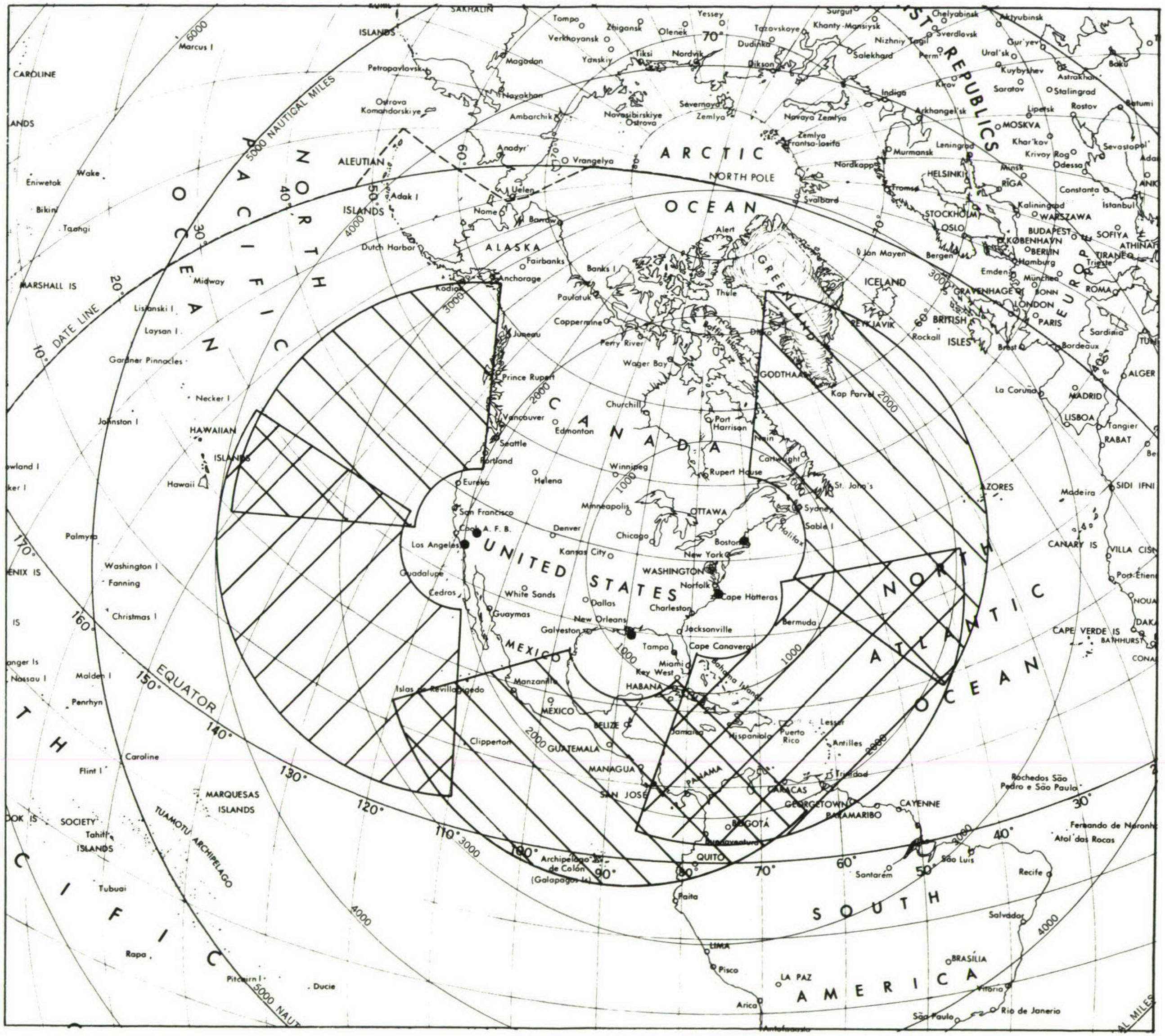

Figure 3 - Geographical coverage pattern for five-station HF radar surveillance system intended to provide coverage to the longest ranges possible ("longest range" alternative).

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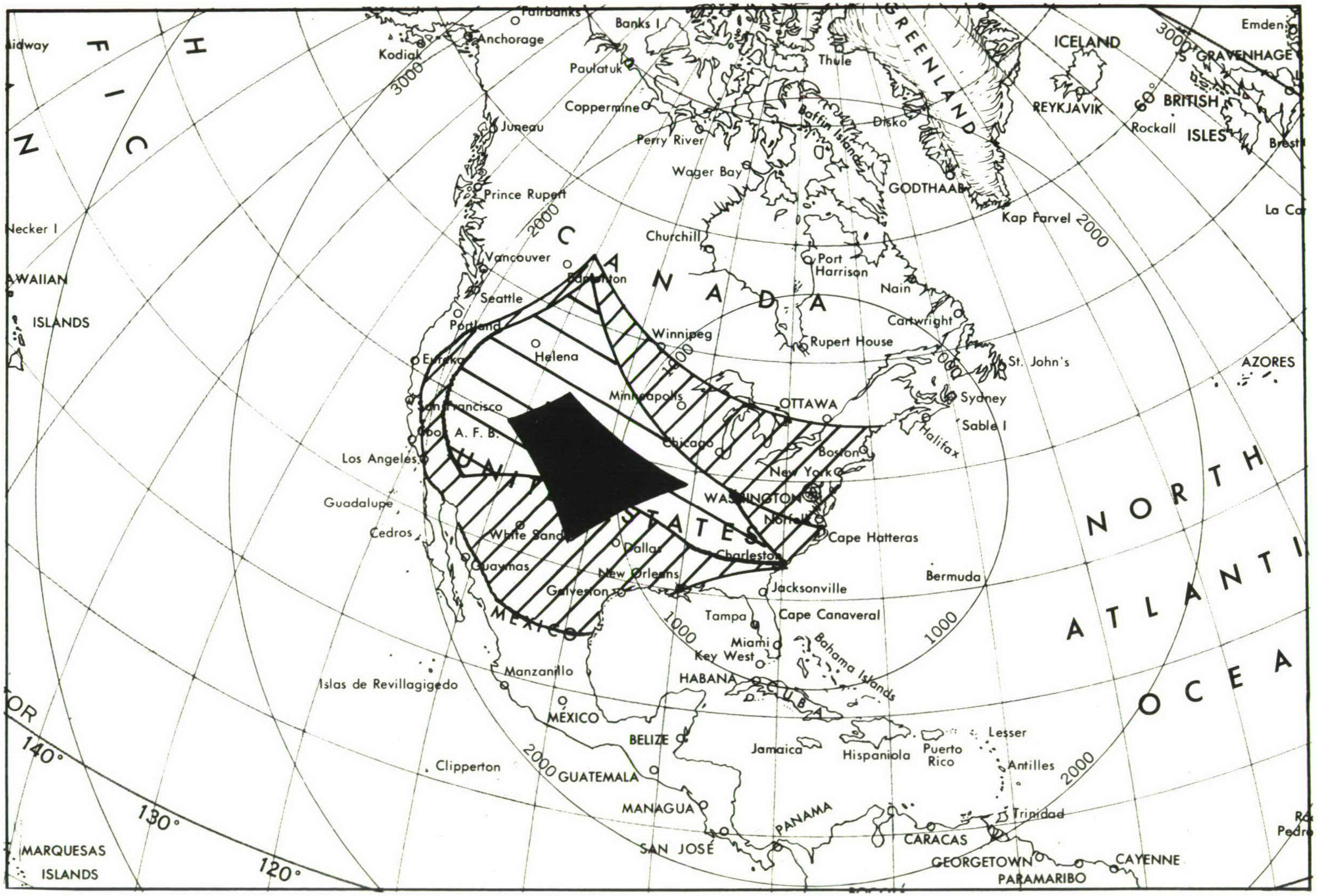

Figure 4 - Areas of North America which would not be vulnerable to undetected long-range SLBM attack under each of the "Coast-Outward" alternatives.

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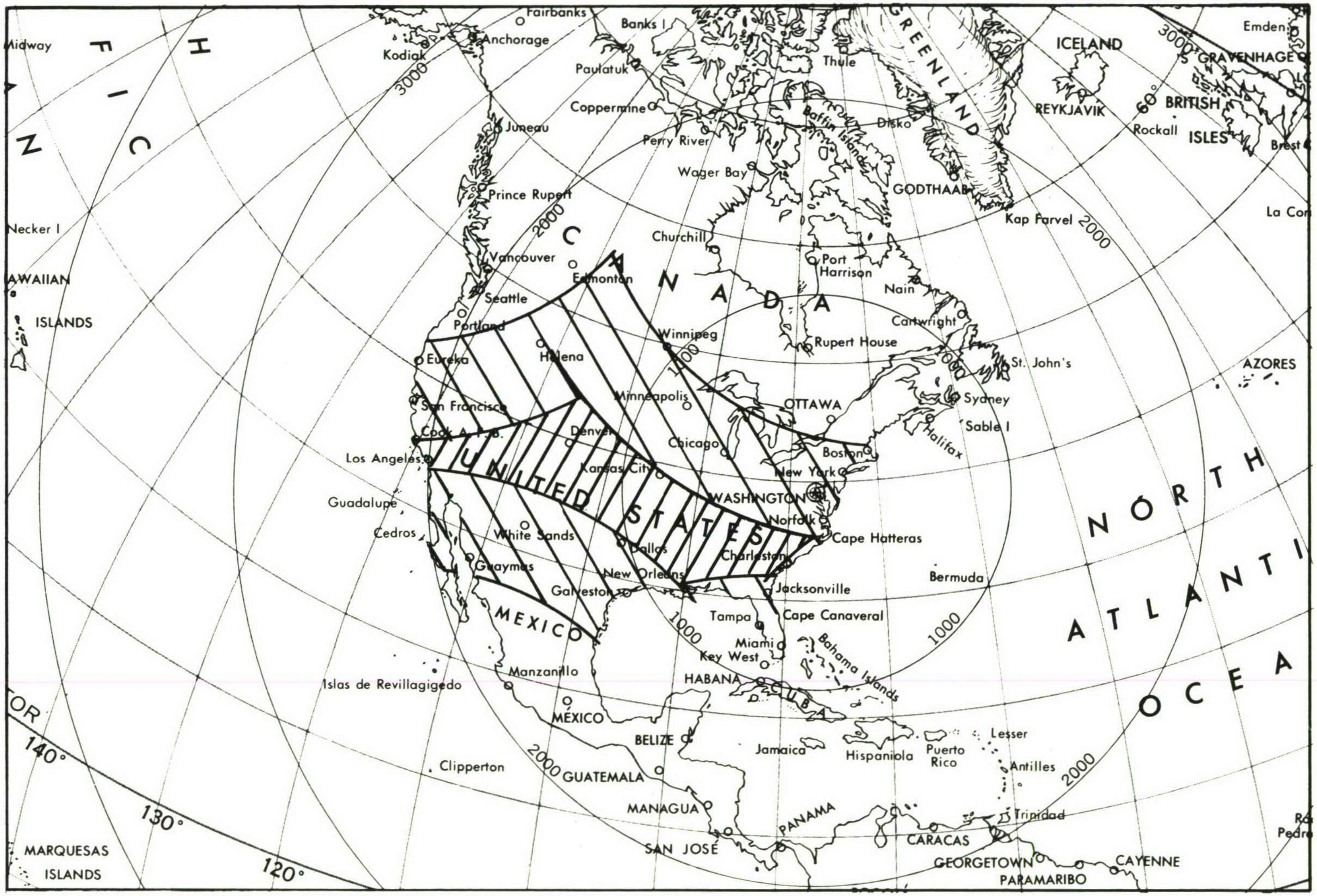

Figure 5 - Areas of North America which would not be vulnerable to undetected long-range SLBM attack under the "longest range" alternative.

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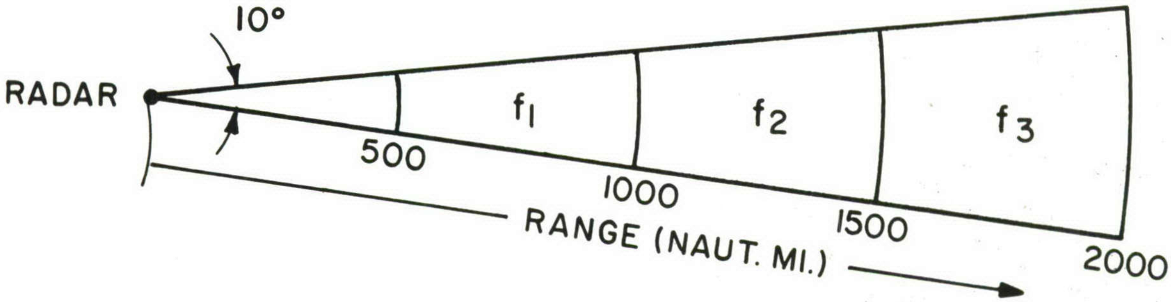

Fig. 6 - Approximate geographical regions in a 10 antenna sector covered by each of the frequencies of a three-frequency surveillance scheme.

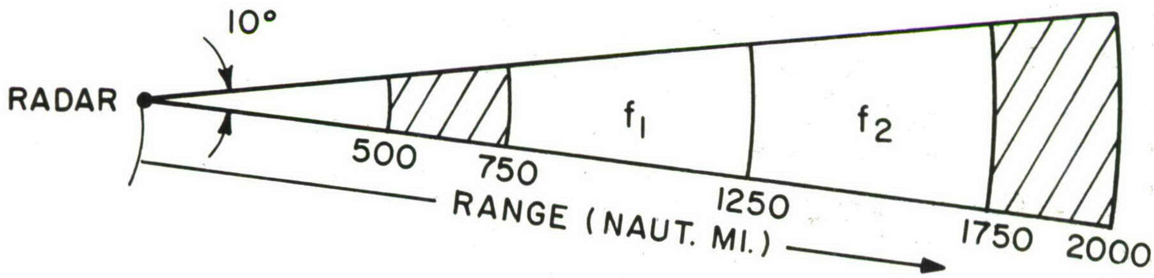

Fig. 7 - Approximate geographical regions in a 10 antenna sector covered by each of the frequencies of a two-frequency surveillance scheme.

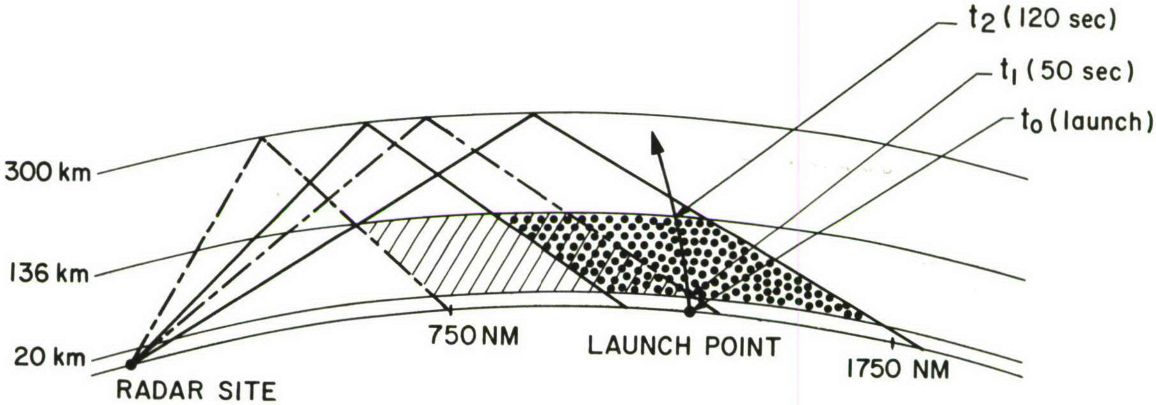

Fig. 8 - Single-hop coverage provided by a two-frequency surveillance scheme under normal daytime ionospheric conditions. A Polaris A3 trajectory is included for reference.

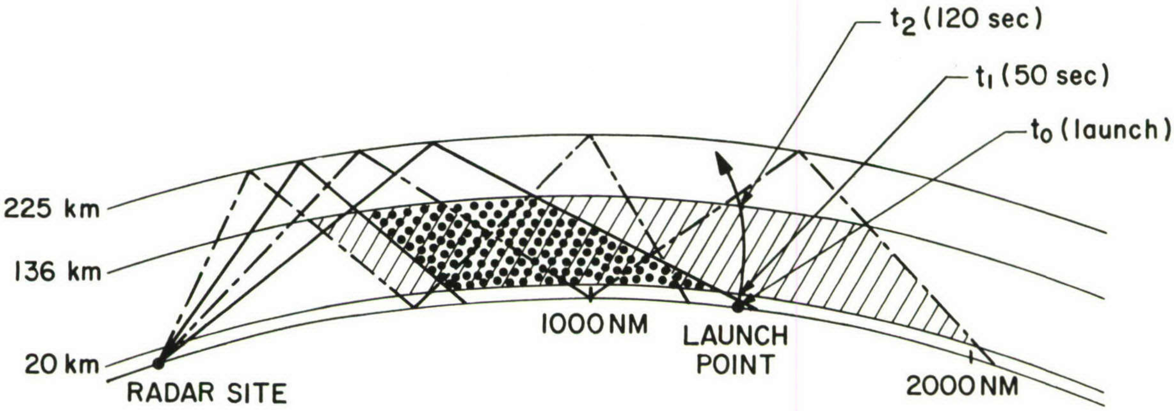

Fig. 9 - Combined single- and double-hop coverage provided by a two-frequency surveillance scheme under winter nighttime ionospheric conditions. A Polaris A3 trajectory is included for reference.

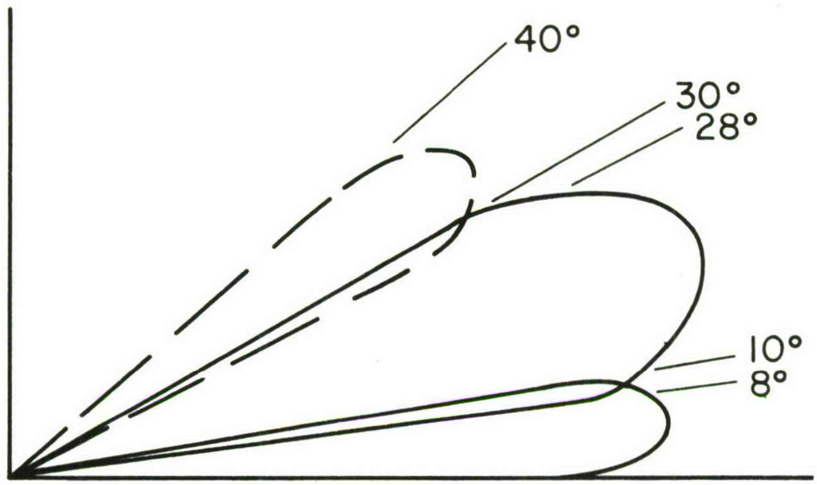

Fig. 10 - Vertical pattern of antenna which would satisfy requirements of HF radar surveillance system.

Table I
Radiation Takeoff Angles For
E- and F-Layer Propagation to Ranges From
500 to 2000 Nautical Miles

	E LAYER	F LAYER				
R \ h′	100	200	250	300	350	400
500	10^0	21^0	26^0	31^0	35^0	38^0
750	5^0	12^0	16^0	20^0	23^0	26^0
1000	2^0	8^0	11^0	13^0	16^0	18^0
1250	7^0 2-Hop	4^0	7^0	9^0	11^0	13^0
1500	5^0 2-Hop	2^0	4^0	6^0	8^0	9^0
1750	3^0 2-Hop	10^0 2-Hop	1^0	3^0	5^0	6^0
2000	1^0 2-Hop	8^0 2-Hop	11^0 2-Hop	1^0	2^0	3^0

h′ = ionspheric layer virtual height in km

R = ground range to target in naut. mi.

Table II
Parameters of Complete HF Radar Surveillance Systems
Designed for Maximum Protection
Against SLBM, SLCM, and Aircraft Attack

Five-station (longest-range) plan	Three-station (coast-outward) plan
1. Four 120° ~~beamwidth~~ COVERAGE antennas in 12 10° segments each and one 100 ~~beamwidth~~ coverage antenna in 10 10° segments.	1. Three 140° ~~beamwidth~~ COVERAGE antennas in 14 10° segments each.
2. 174 coverage subintervals requiring a total of 58 power sources.	2. 126 coverage subintervals requiring a total of 42 power sources.
3. Geographical coverage from 500 naut. mi. beyond coast.	3. Geographical coverage from coast to 1500 naut. mi. beyond coast.
4. Requires coastal line-of-sight radars to fill close-in gaps in surveillance coverage.	4. Does not require coastal line-of-sight radars for gap-filling in surveillance mode.

5. Basic power source capable of 5 to 10 mw peak power, 100 kw average power.
6. Flexibility provided by modular construction, permitting use of multiple power sources on single antenna element if desired.
7. 9-second scan time, providing 3-second dwell time in each geographical subinterval.
8. Basic antenna element of 10° beamwidth, 25 db gain, frequency independent from 5 to 28 Mc/s.
9. Excitation source capable of changing excitation frequency rapidly between 5 and 28 Mc/s.
10. Data processing to provide rough range (± 20 naut. mi.) and azimuth (± 1° to 2°) data plus approach/recede information.
11. Requires complementary line-of-sight radars to provide fine trajectory data and impact prediction (some such information possible with this system if general performance characteristics of missile are known).

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APPENDIX A
NRL SIGNAL PROCESSING FOR LONG RANGE. OVER THE HORIZON RADAR DETECTION

J. M. Headrick
U.S. Naval Research Laboratory
Washington, D. C.

I. INTRODUCTION

A brief historical sketch may aid in explaining the NRL work on signal processing. In the late 1940's NRL*was investigating in two principal areas: (1) Study of rocket exhausts from an electromagnetic wave point of view and (2) Extending radar range by application of narrow frequency band signal processing techniques. This paper will deal mainly with (2); however the two investigative areas have been complementary at times.

The useful application of narrow-band filtering to radar signals requires exact definition of the emitted signal and knowledge of its modification by the target and the propagation path. The HF portion of the electromagnetic spectrum looked attractive after some study and experimental work and consideration of applicable work of others. The Air Force sponsored work by Lincoln Labs and Raytheon was especially helpful. By the early 1950's NRL had a very modest experimental HF radar (MUSIC) in operation. With this radar system the earth backscatter was studied from two points of view, that is, how to co-exist with it and what could be inferred from it as to the nature of ionospheric paths. As a result of this work it was concluded that HF transhorizon radar employing narrow-band filtering was feasible.

R. M. Page of NRL suggested a signal processor in 1954 that showed promise of converting the aforementioned feasibility to practicality. This was a magnetic drum storage and time compression technique. By using time compression a relatively modest number of filters would be required and fairly sophisticated filter matching would be achievable. Based on these ideas the General Electric Company provided from NRL specifications a low-power radar system, less antenna and duplexer, for NRL. Results obtained using this system as well as continued development supported the practicality of HF transhorizon radar. In 1961 an RCA-developed storage disc, antennas, and high power amplifier were added to the low power system. These components plus many directly due to NRL constituted the MADRE radar on Chesapeake Bay. With this radar system transhorizon aircraft detection and time-range tracking have been done at distances as close as 500 and as far as 2500 naut. mi. Many missile launches on the Atlantic and Pacific Ranges have been detected and investigated.

*Radar Techniques Branch

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II. EARTH BACKSCATTER

In the ensuing discussion, coherent pulse doppler methods will be assumed; that is, frequency translations are made with reference to the transmitted carrier.

The sketch shown in Fig. 1 is intended to illustrate typical relative signal levels for an HF system using pulse lengths on the order of a millisecond. The top represents a transmitted signal and the earth return of amplitude E at a zero frequency i-f. In the second trace the earth returns have been removed and the desired signal shown with amplitude e. Clutter to signal voltage ratios of 10^4 can be common for aircraft targets.

In Fig. 2 a 7-minute doppler history of earth backscatter is shown. The beamwidth was 10°; the range gate was 40 naut. mi. at about 1900 naut. mi.; and the resolution bandwidth 1/10 cps. This representation indicates the extent of the top 20 db of backscatter. It isn't fair to call this a typical analysis but nevertheless the depicted frequency extent is common. This analysis shows that the bulk of energy is within one cps from the carrier. The frequency-time stability can also be inferred. Figures 3 and 4 show the results of a Fourier-type analysis taken a little later in the day from that of Fig. 2 and with different look directions.

Once in possession of considerable data similar to that shown, the NRL approach to the backscatter problem was to use rejection filters with a notch width sufficient to contain the usual backscatter frequencies. In Fig. 5 the radar-emitted spectrum is shown at the top and below two different rejection techniques. In the center case the carrier is suppressed, from near the carrier to plus and minus one-half the repetition rate passed and everything else suppressed. This technique was the first used at NRL; it requires time gating prior to its application if range information is to be preserved; and it has the bonus feature that approach and recede targets can be separated if the two sideband filters have separate outputs. The bottom transfer characteristic of Fig. 5 is that of a bandpass filter, appropriate to the desired time or range definition and with narrow nulls placed on the carrier and at each repetition rate sideband. This form of filtering attained either with cancellation delay lines or with simple multiple pole filters has been used in most of NRL work. Figures 6a, 6b and 6c show a missile launch as seen with the rectified output of these filters. This readout is a "Z" plot of both exhaust echoes and prompt perturbations. A high repetition rate was used and there is consequent range ambiguity.

III. GATING AND PACKING PULSE DOPPLER SIGNALS

Across the top of Fig. 7 is sketched a train of transmitted signals, T, and two echoes, 1 and 2. Employment of a short range gate at the times of echo No. 1 would have an output like the second line. A gate at echo No. 2 would have an output similar to the third line. On the fourth line is shown the result of packing the range-gated samples of echo No. 2. This is the essence of what has been called the MADRE system. Its salient feature is that cw filtering techniques can be used and there is lots of time in which to use them.

Here a short digression will be made. Frequency analysis of range-gated outputs such as the second and third lines of Fig. 7 can be easily made. Figures 8a and b are analyses of a Minuteman launch made with a Kay vibralyzer. The early velocity line echoes and later diffuse doppler frequency echoes can be distinguished. The chief disadvantage of this form of analysis and presentation is that it either takes lots of time or lots or range gates and filters.

Now again referring to Fig. 7, the bottom sketch illustrates the form of storage used at NRL. The range gates are narrow, less than a microsecond, and the packing such that a time compression ratio of about 82,800 is used. Considerable flexibility is possible with this type of processor. However, in general, amplitude samples are taken in time no farther apart than a radar pulse width. Different storage times are possible, time running from present to length of storage time in the past. During each repetition rate period and for each range gate one new sample is added and the oldest erased. Since the time delay for each sequence of samples is known, range can be indicated.

IV. ANALYSIS AND PRESENTATION

In Fig. 9 doppler histories are given for a Titan II. Three range gates were employed and 6 minutes of storage time. The doppler resolution is about one cps. This was accomplished by sweeping a 90-kc bandpass filter across the spectrum at a 2-second rate - possible because of time compression. This missile was approaching so that the discrete velocity line from low-altitude detection appears at the most distant range. The latter diffuse doppler returns come in the closer range gates. This form of presentation should be visualized as a scope display with time "now" at the extreme right and time into the past running to the left.

The most used form of analysis and presentation has been one of doppler (or range rate) versus range. The usual technique has been to employ about 22 range samples taken with about 240 naut. mi. spacing. The storage time used has been 20 seconds. This form of operation was intended to approximate matched filtering for aircraft targets. Resolution bandwidths of about 1/3 or 1/10 cps have been used; that is, either an 8-kc or 40-kc sweeping filter has performed the spectrum analysis at a two-second rate. Figure 10 shows a look at the aircraft population beyond Denver.

This doppler versus range form of presentation is sensitive for missile detection. With parameters as mentioned above, of course, it does not represent matched filtering (unless perhaps the operator is included). The range discreteness of missile echoes plus the frequency smears due to both acceleration and the diffuse doppler character of returns provide a distinctive signature. Figure 11 illustrates the detection of an SLBM launch with the doppler versus range form of presentation. This was AMR Test 0238 of this year. A picture was taken for approximately every second doppler analysis.

The continuous availability of a compressed doppler history in the storage device permits changing doppler (velocity) filtering or acceleration gating. An experimental acceleration gate processor (with a small number of gates) has been developed and tested. This technique shows promise for missile detection.

V. DISCUSSION

There have been some recent expressions of interest in missile target scintillation. The forms of analysis described above provide a form of scintillation study. When desired, a true Fourier form of analysis can be performed (amplitude versus frequency) and this has been done on occasion.

In summation, narrow-band doppler spectrum analysis and display are attractive in HF radars. Target recognition and definition are strong features. Linearity in the receiver and processor are essential for this form of analysis and present the most serious limitation in present day equipment; the magnetic disc storage used at NRL has about 30-db dynamic range. Studies have been made under NRL contracts with both G.E. and RCA aimed at extending storage dynamic range. By using digital techniques a 60-db processor seems to be attainable.

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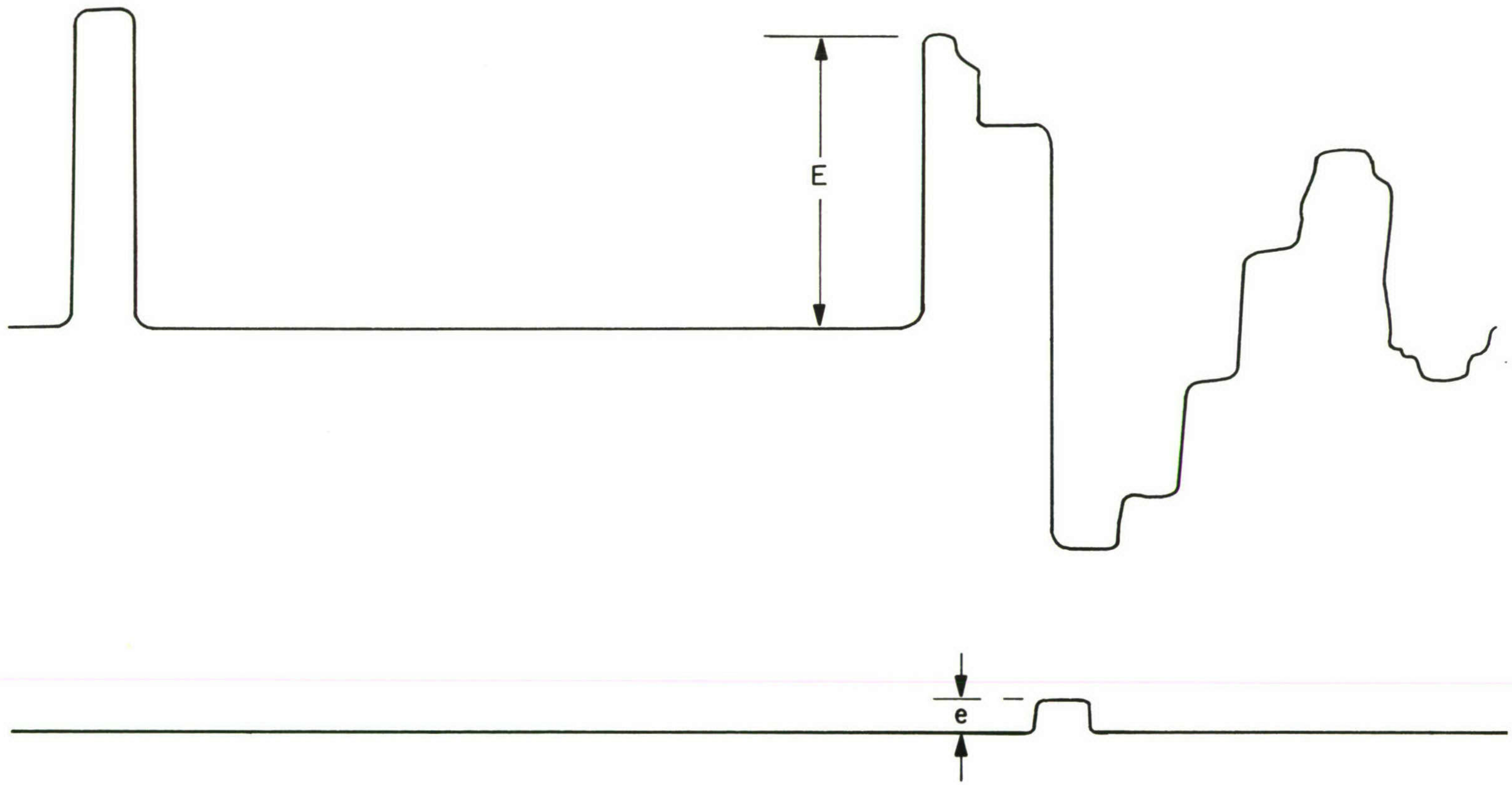

$$\frac{E}{e} = 10^4$$

Figure A1 - The top sketch is intended to represent a single coherent pulse doppler radar interpulse period. The transmitted signal is at the extreme left and the earth backscatter echo is toward the right. The lower sketch shows how the top should look after clutter filtering and amplification. A representative clutter to signal ratio is given.

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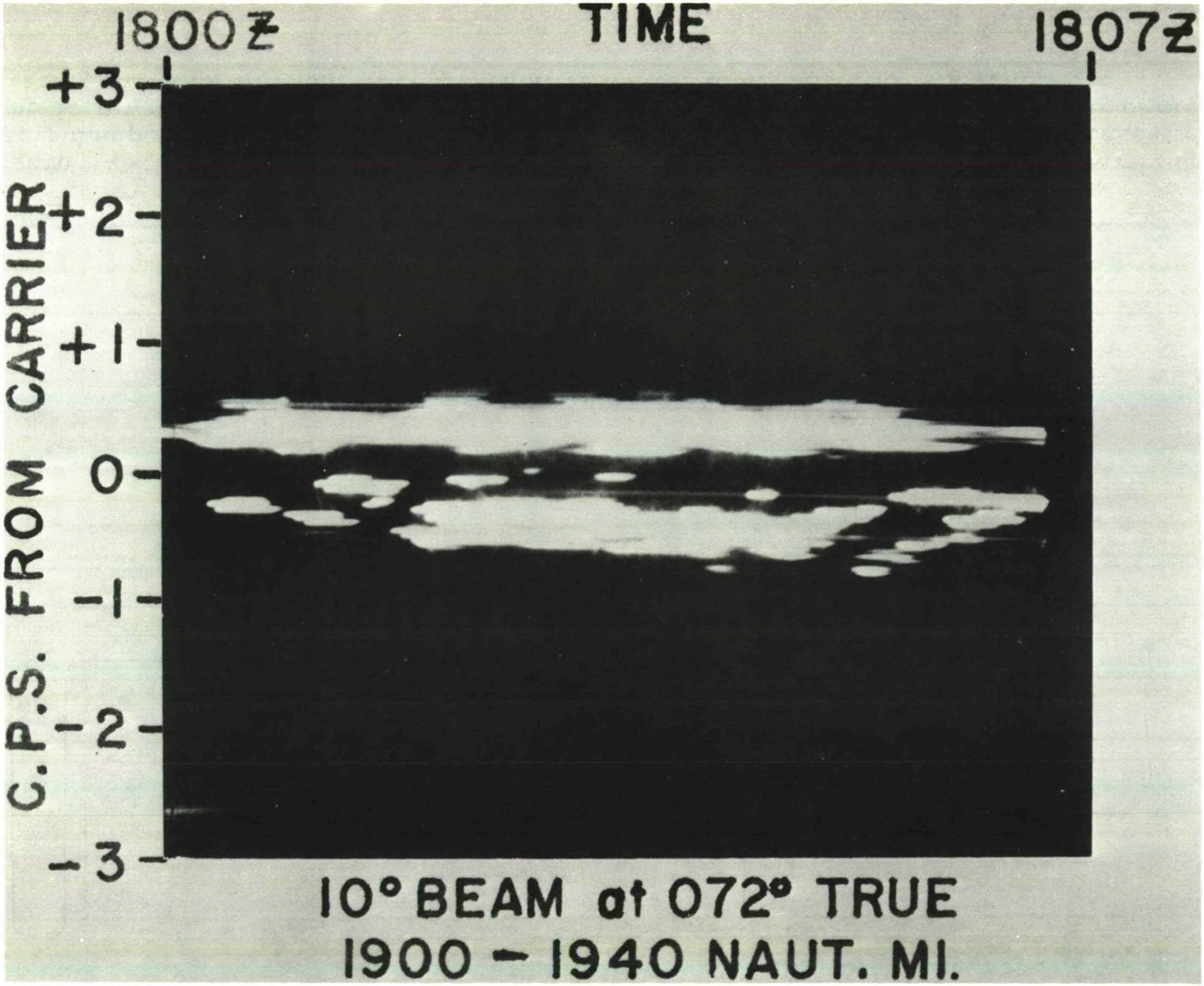

Figure A2 - A seven-minute range-gated doppler history of earth backscatter. Frequency was 18 Mc. Resolution bandwidth of filter was one-tenth cycle per second.

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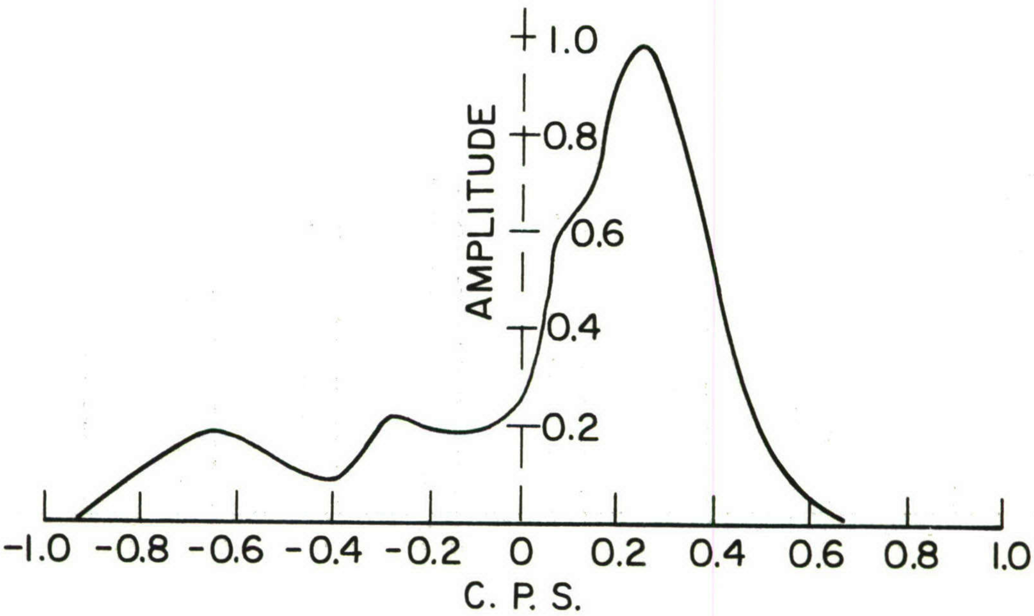

Figure A3 - Fourier-type analysis with one-tenth cycle bandwidth filter taken of a 20-second sample of backscatter. Frequency with 18 Mc, bearing 082°T, 10° beamwidth and sample 20-mile length range gated at 1400 naut. mi.

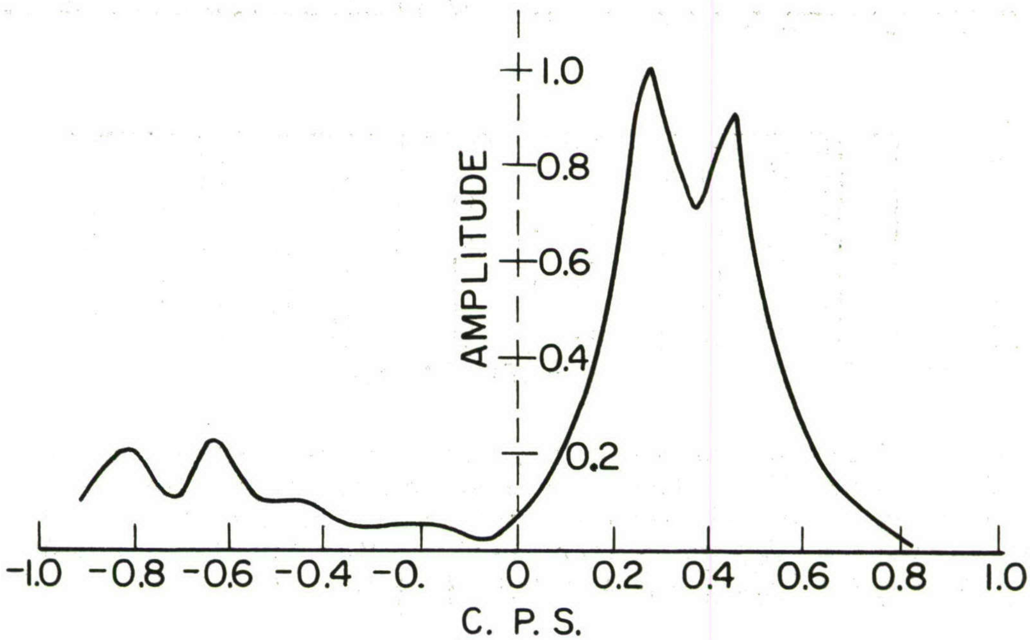

Figure A4 - Fourier-type analysis of backscatter as described for Fig. 3 except taken a few minutes later in time.

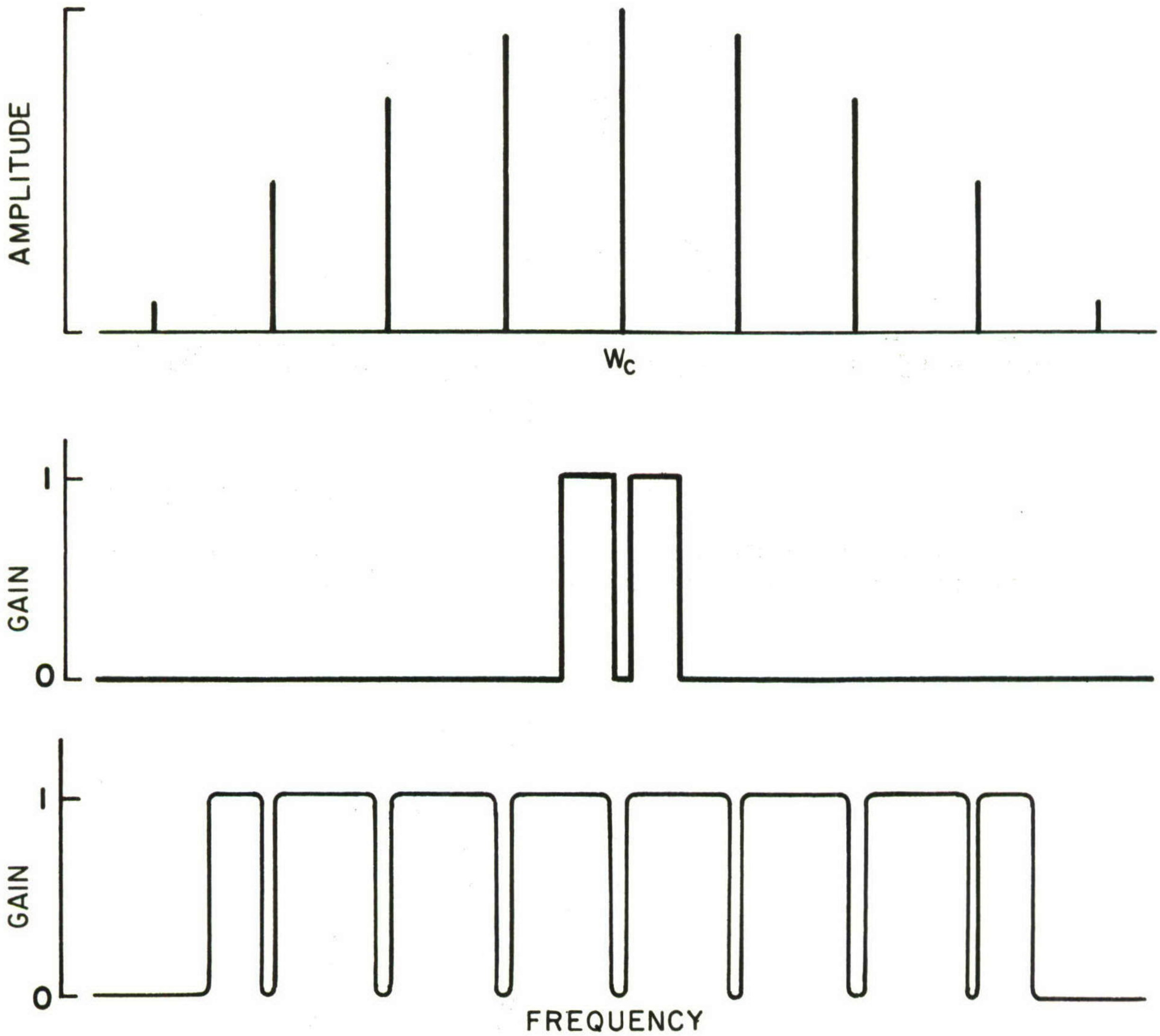

Figure A5 - The top sketch is of the radar emission given as amplitude versus frequency plot. The middle sketch shows a filter gain versus frequency characteristic with a notch on the carrier for backscatter suppression. The bottom sketch is of a filter for the suppression of backscatter near the carrier and repetition rate lines.

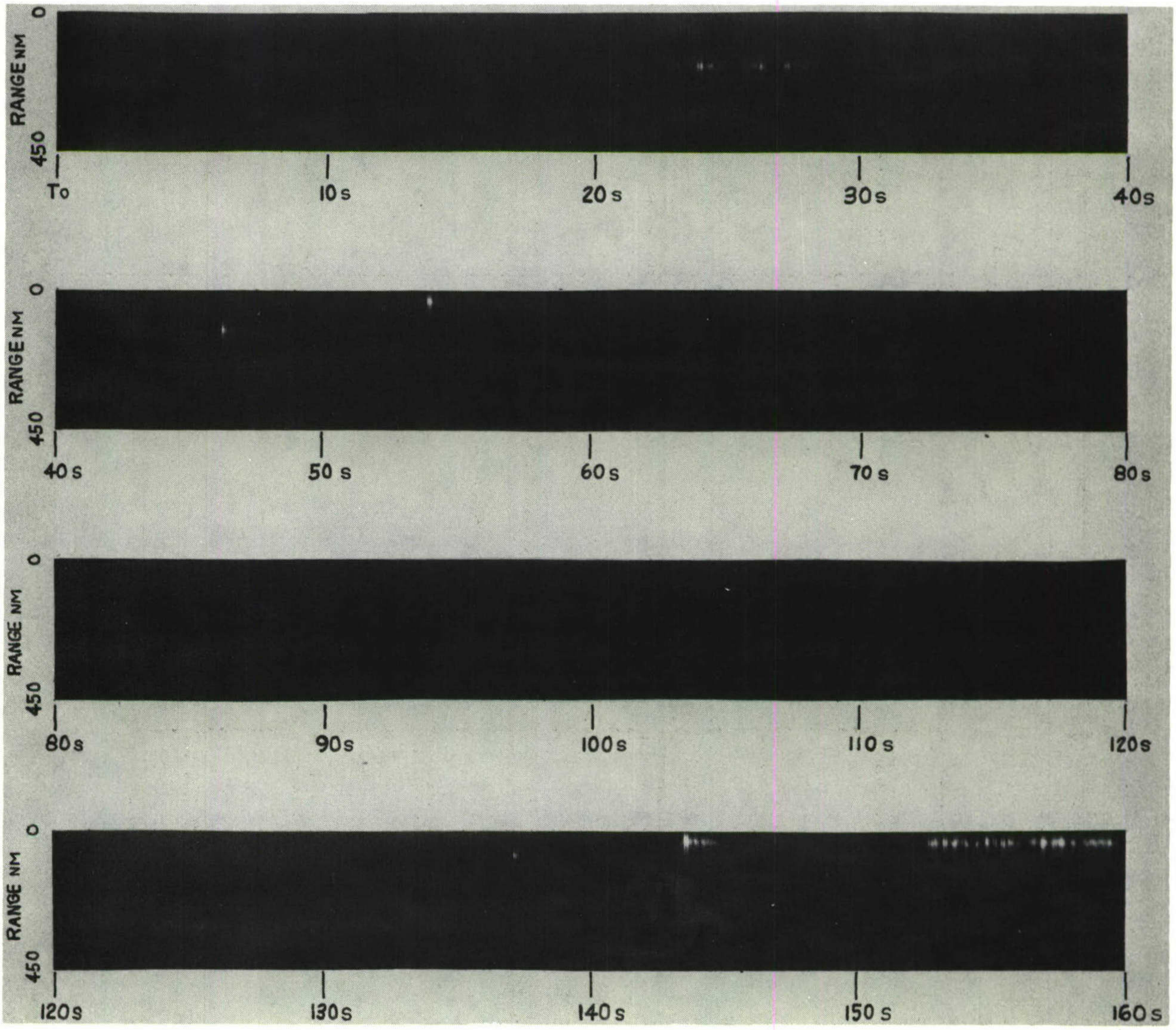

Figure A6a - AMR 1361, 5/23/61, 11:37:33 P.M. EST. A Titan observed using a 13.7-Mc frequency and a 180-pps repetition rate. This shows the rectified output from the backscatter rejection filters as intensity against time after launch and range. The responses are of prompt perturbations and exhaust reflections in the form of a range ambiguous "Z" plot.

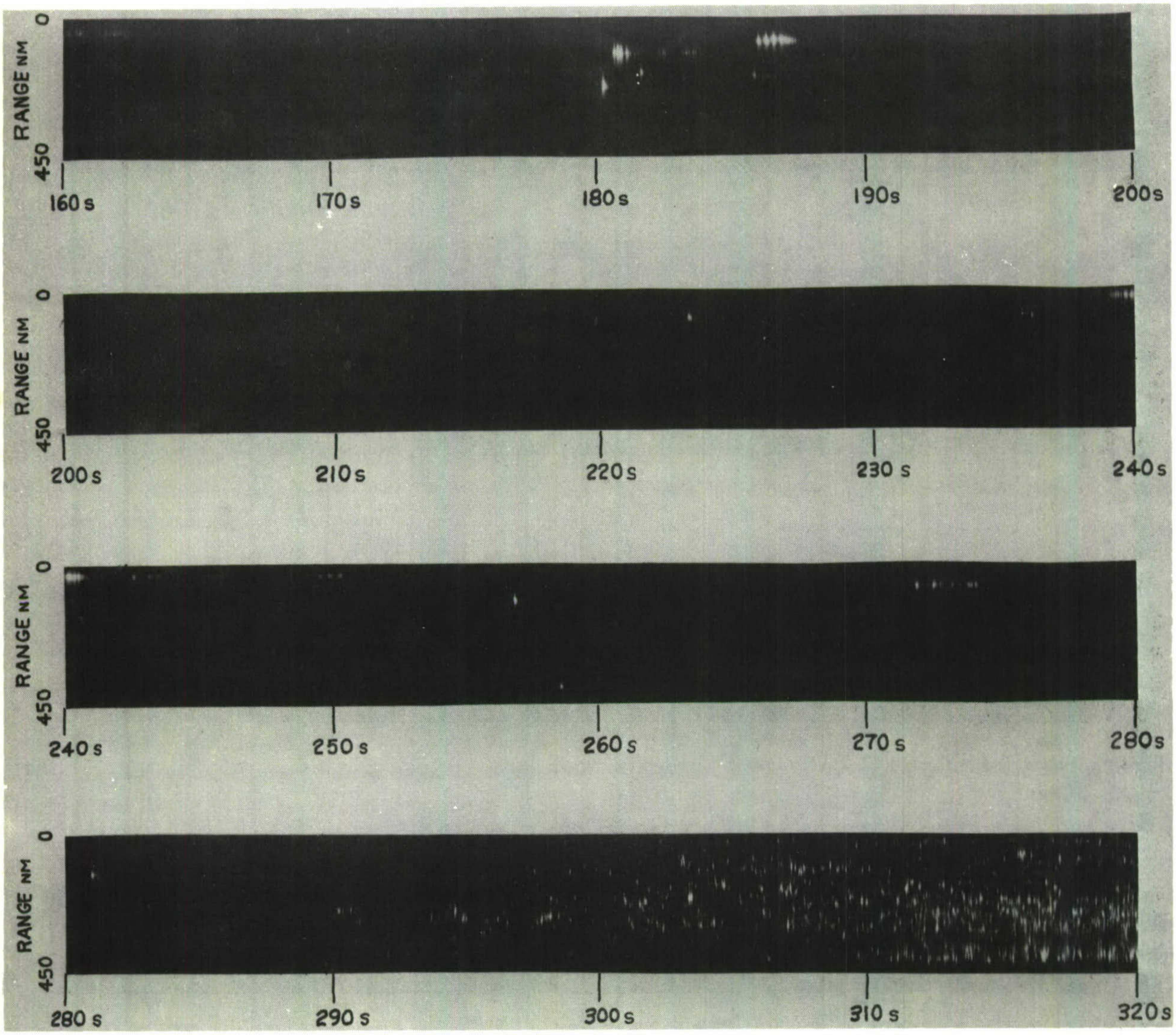

Figure A6b (Continuation of Figure A6a) - AMR 1361, 5/23/61, 11:37:33 P.M. EST. A Titan observed using a 13.7-Mc frequency and a 180-pps repetition rate. This shows the rectified output from the backscatter rejection filters as intensity against time after launch and range. The responses are of prompt perturbations and exhaust reflections in the form of a range ambiguous "Z" plot.

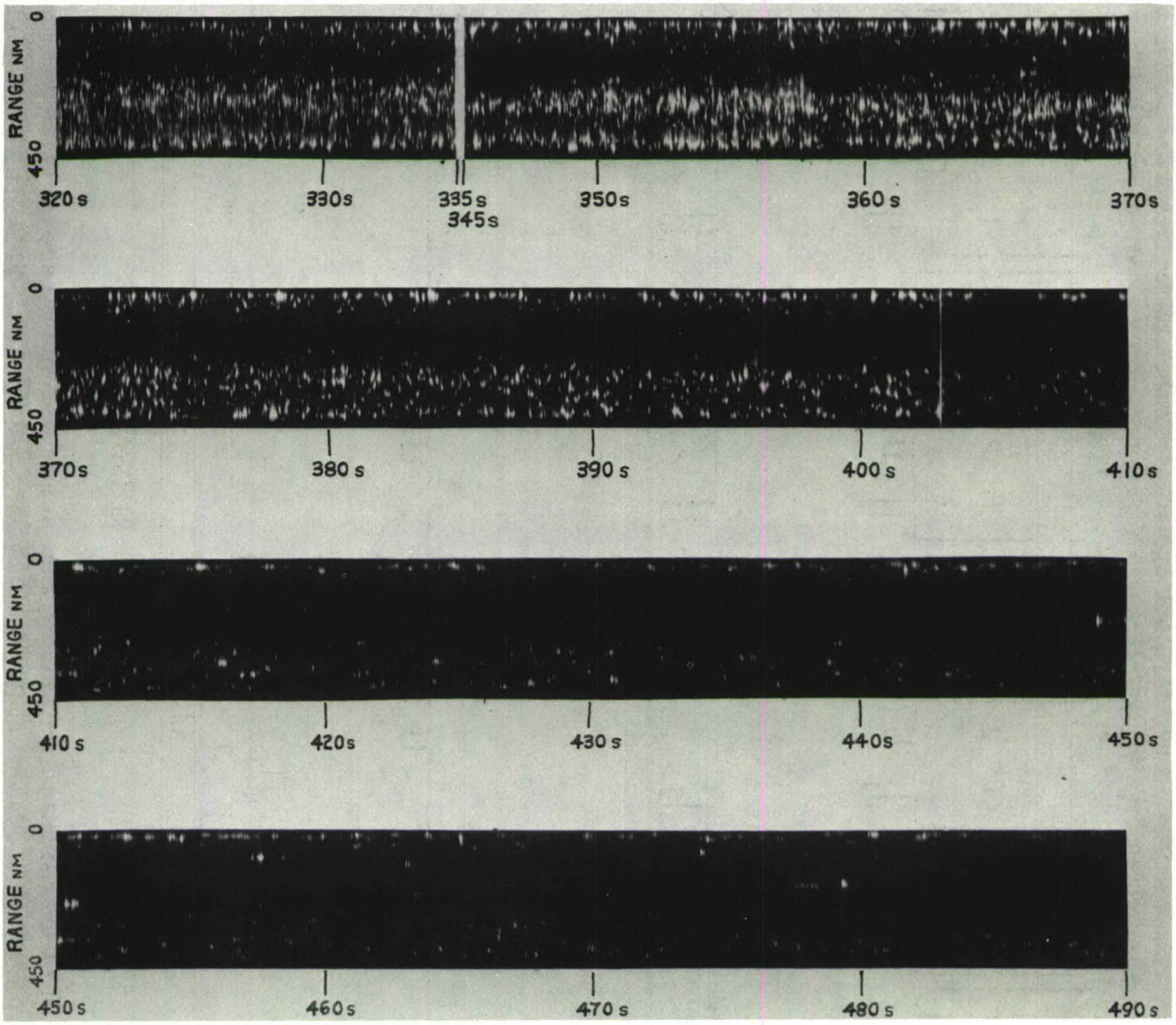

Figure A6c (Continuation of Figure A6b) - AMR 1361, 5/23/61, 11:37:33 P.M. EST. A Titan observed using a 13.7-Mc frequency and a 180-pps repetition rate. This shows the rectified output from the backscatter rejection filters as intensity against time after launch and range. The responses are of prompt perturbations and exhaust reflections in the form of a range ambiguous "Z" plot.

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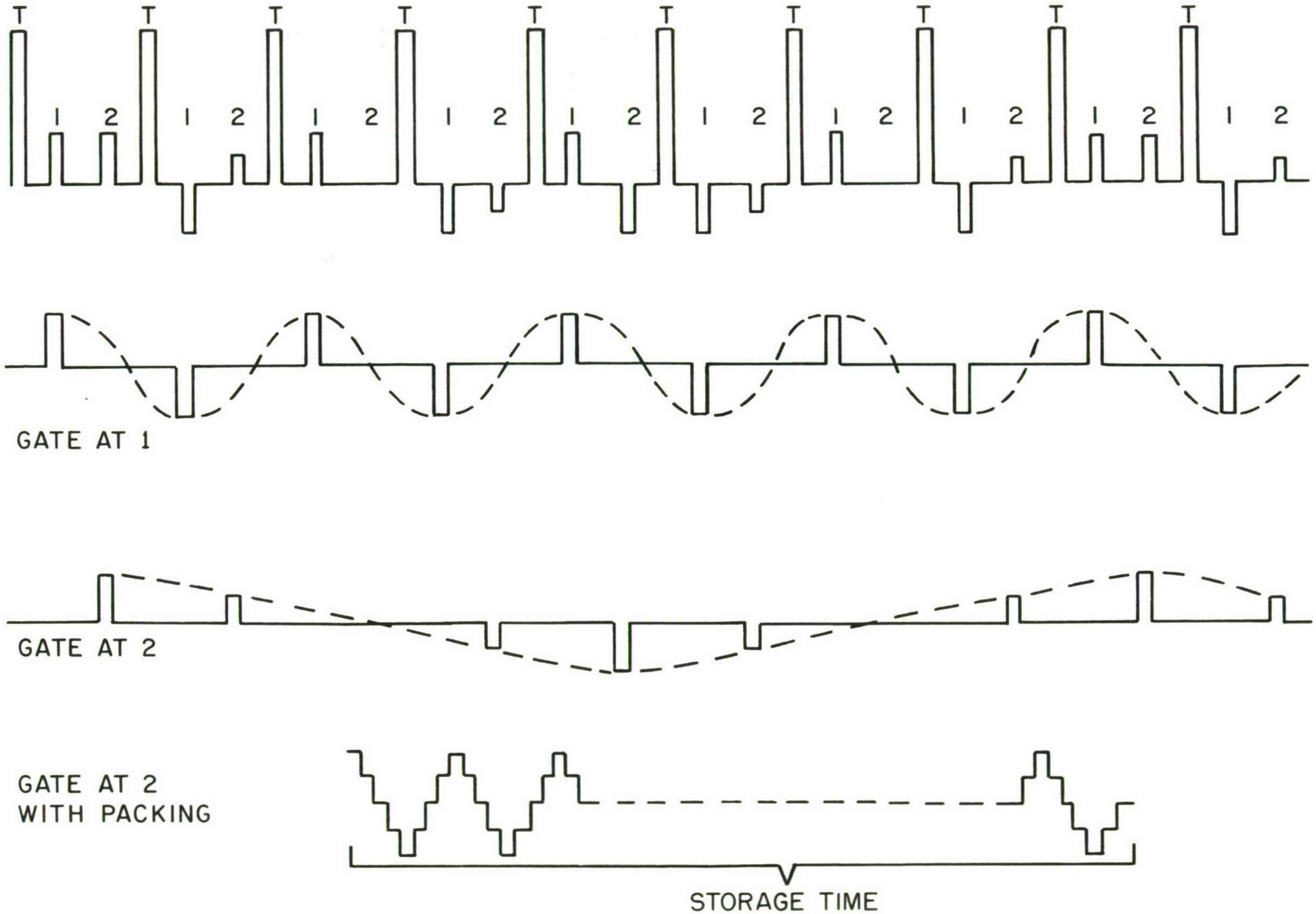

Figure A7 - A train of transmitted pulses, T, and echoes, 1 and 2, shown at zero frequency i-f. The results of range gating at the times of echoes 1 and 2 are shown as the second and third train of pulses. At the bottom the train of echo 2 pulses are shown packed in time.

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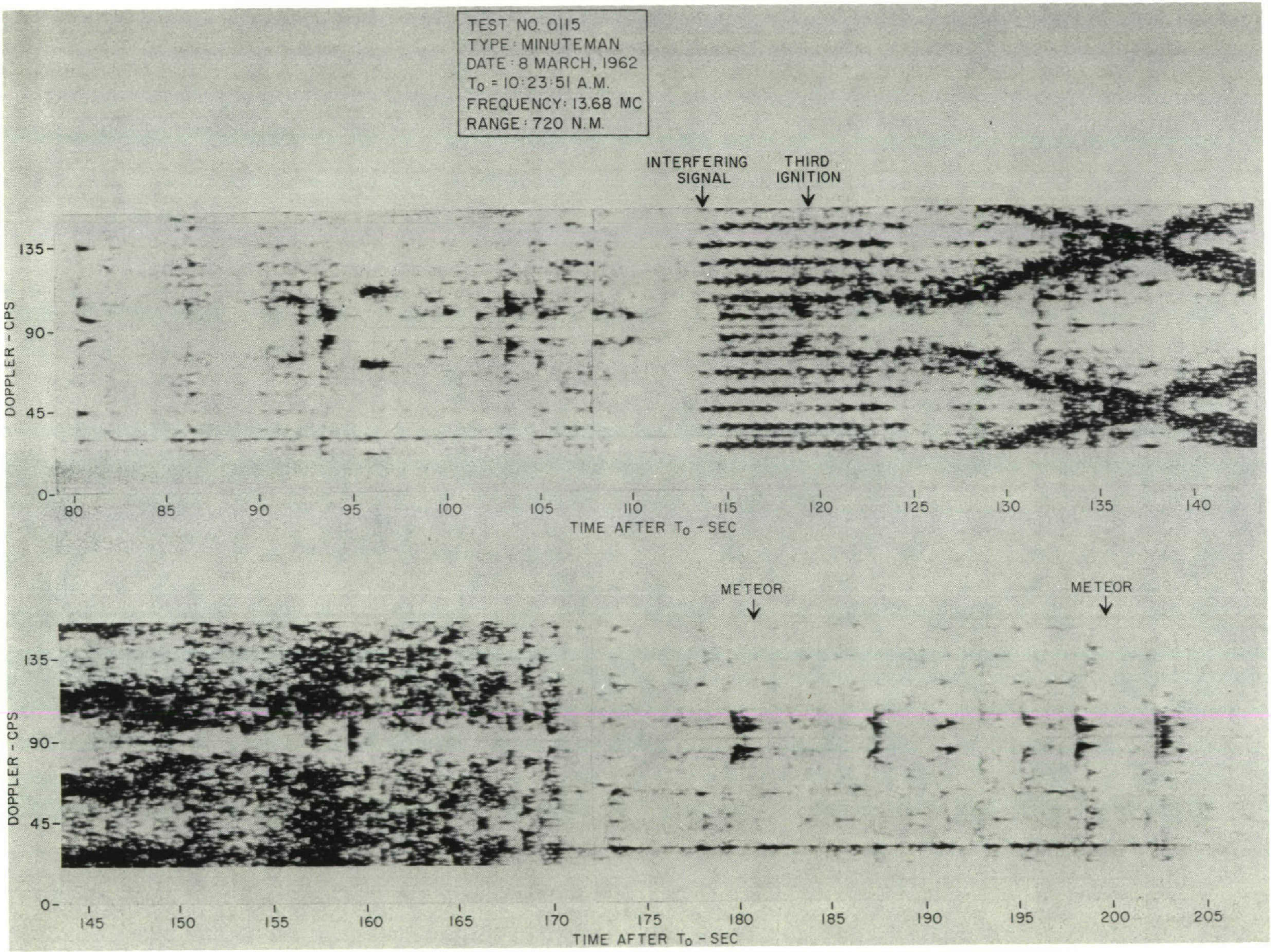

Figure A8 - Range-gated doppler versus time analysis of a Minuteman. Since a repetition rate of 90 pps was used, doppler folds occur every 45 cps. Frequency analysis made with a Kay Vibralyzer.

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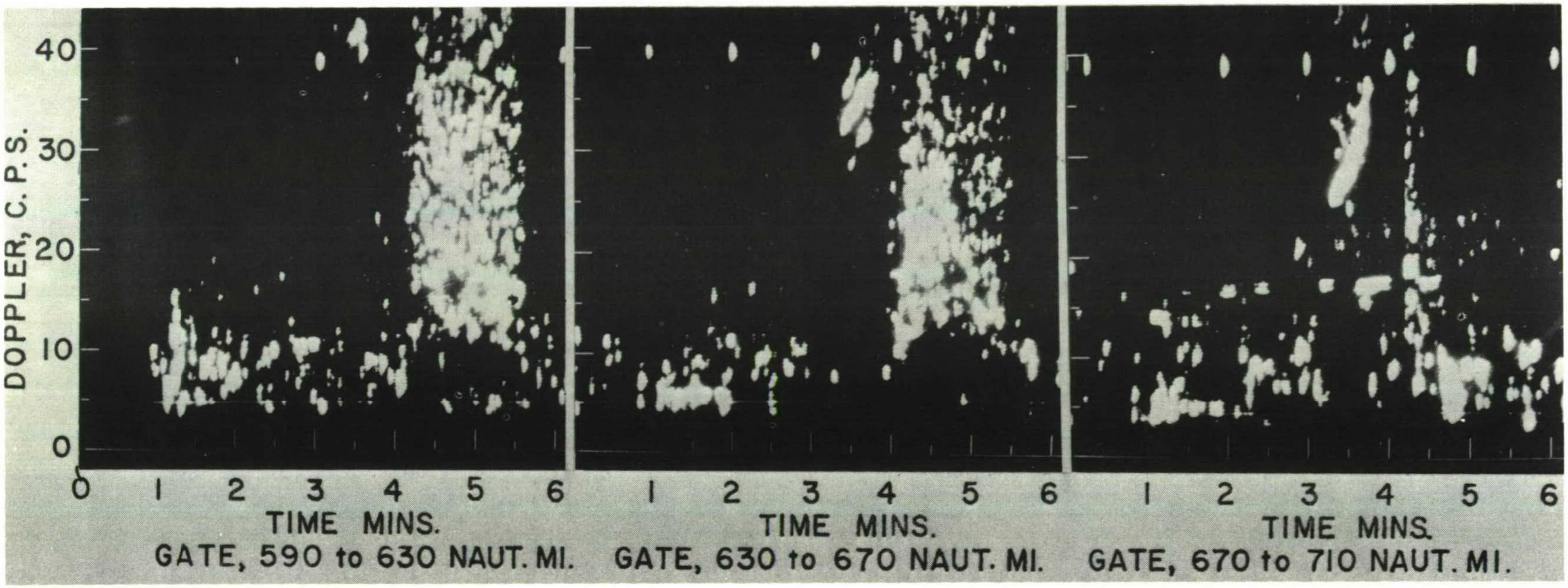

Figure A9 - Doppler histories of AMR 0275, 4/8/64, 11:00:03 A.M. EST. This shows the results of frequency analysis of range-gated, time-compressed, stored zero frequency i-f.

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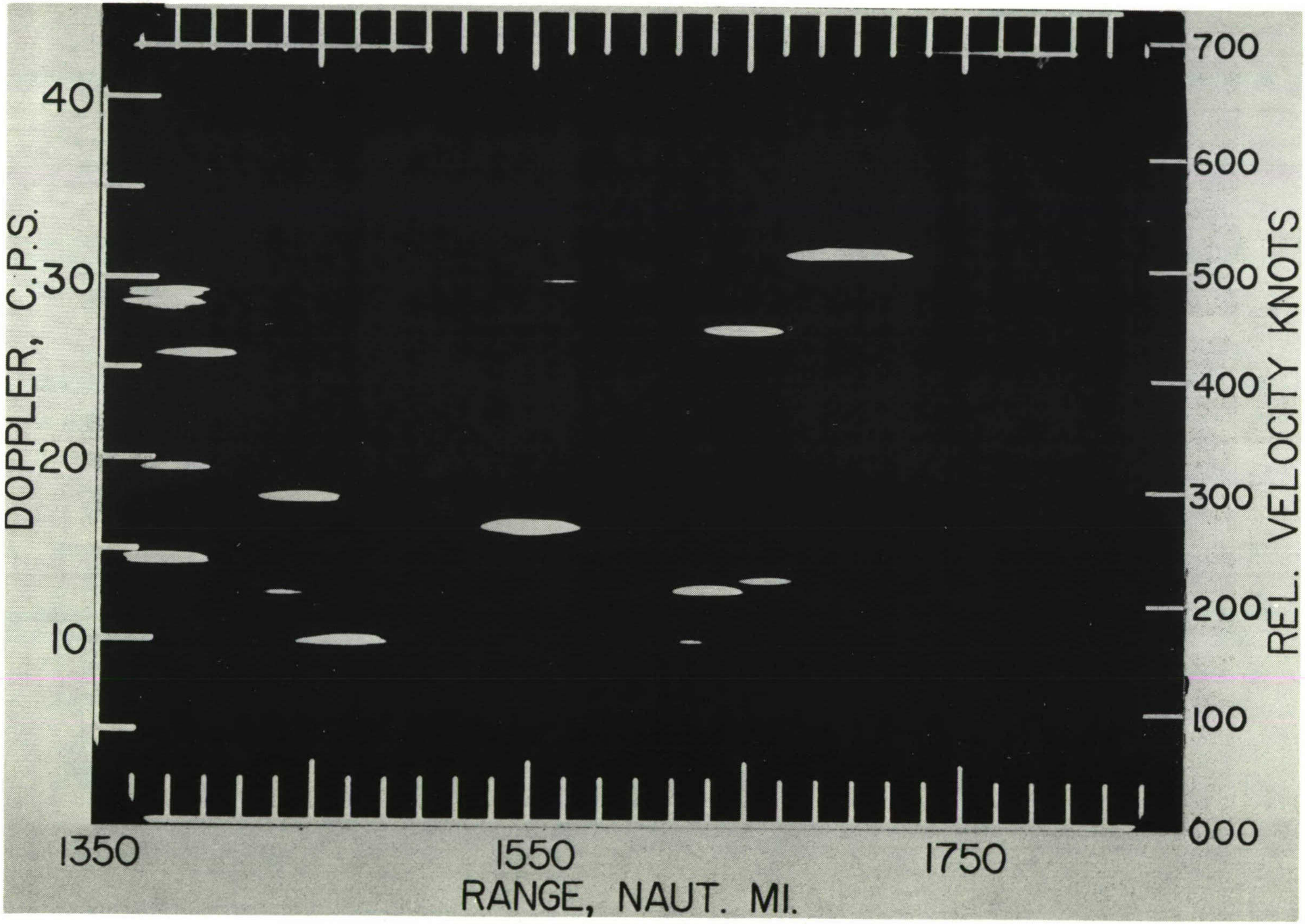

Figure A10 - Range rate or doppler versus range display of interval between 1350 and 1800 naut. mi. west of NRL - CBA. A number of aircraft returns can be seen.

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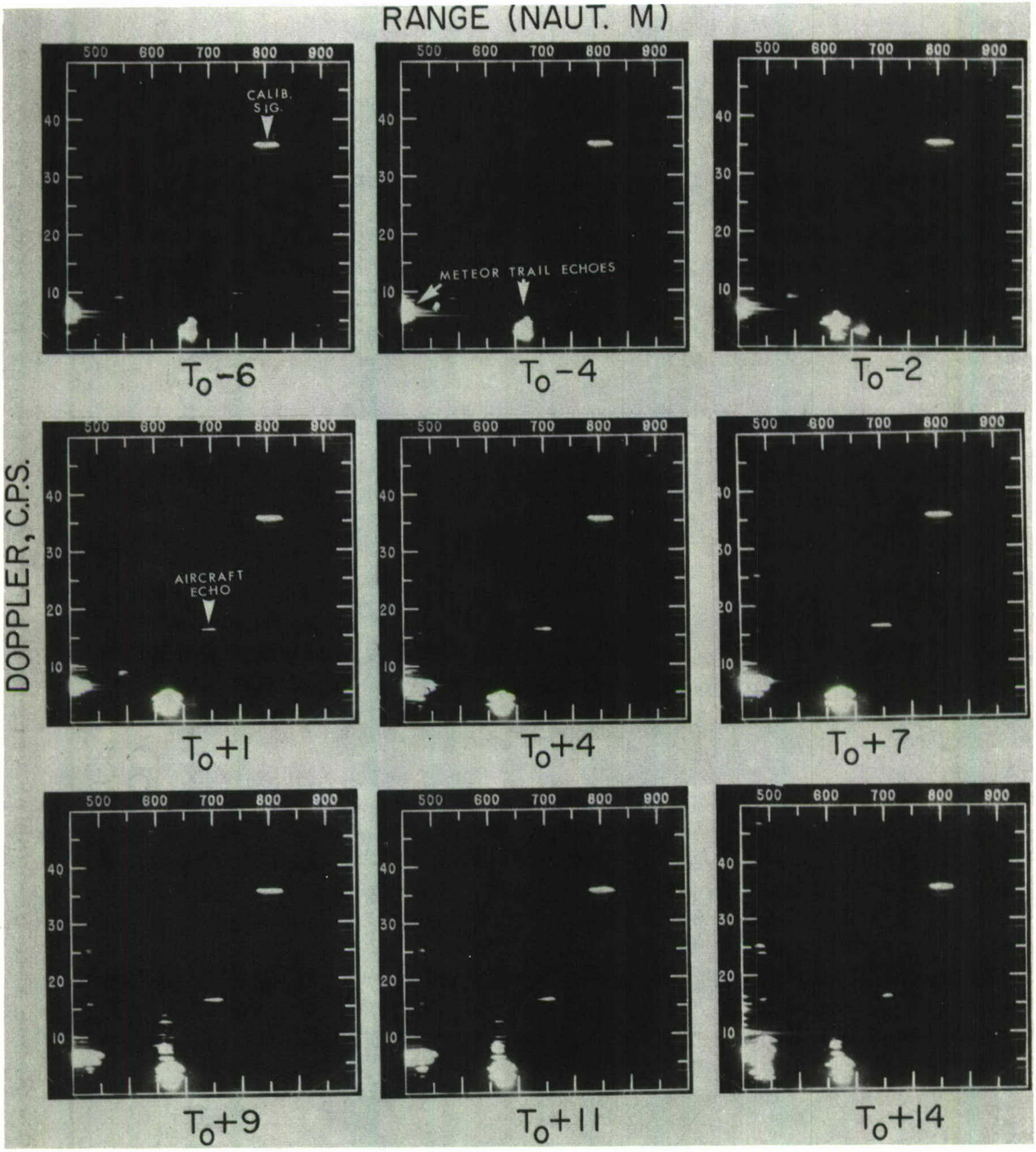


Figure A11a - A sequence of pictures taken of the doppler versus range display. These are for observations of an A-2 Polaris launch, AMR 0238, 2/6/64, T_o 11:41:08 A.M. EST. The frequency was 19.27 Mc and a high E_s layer was used for refraction.

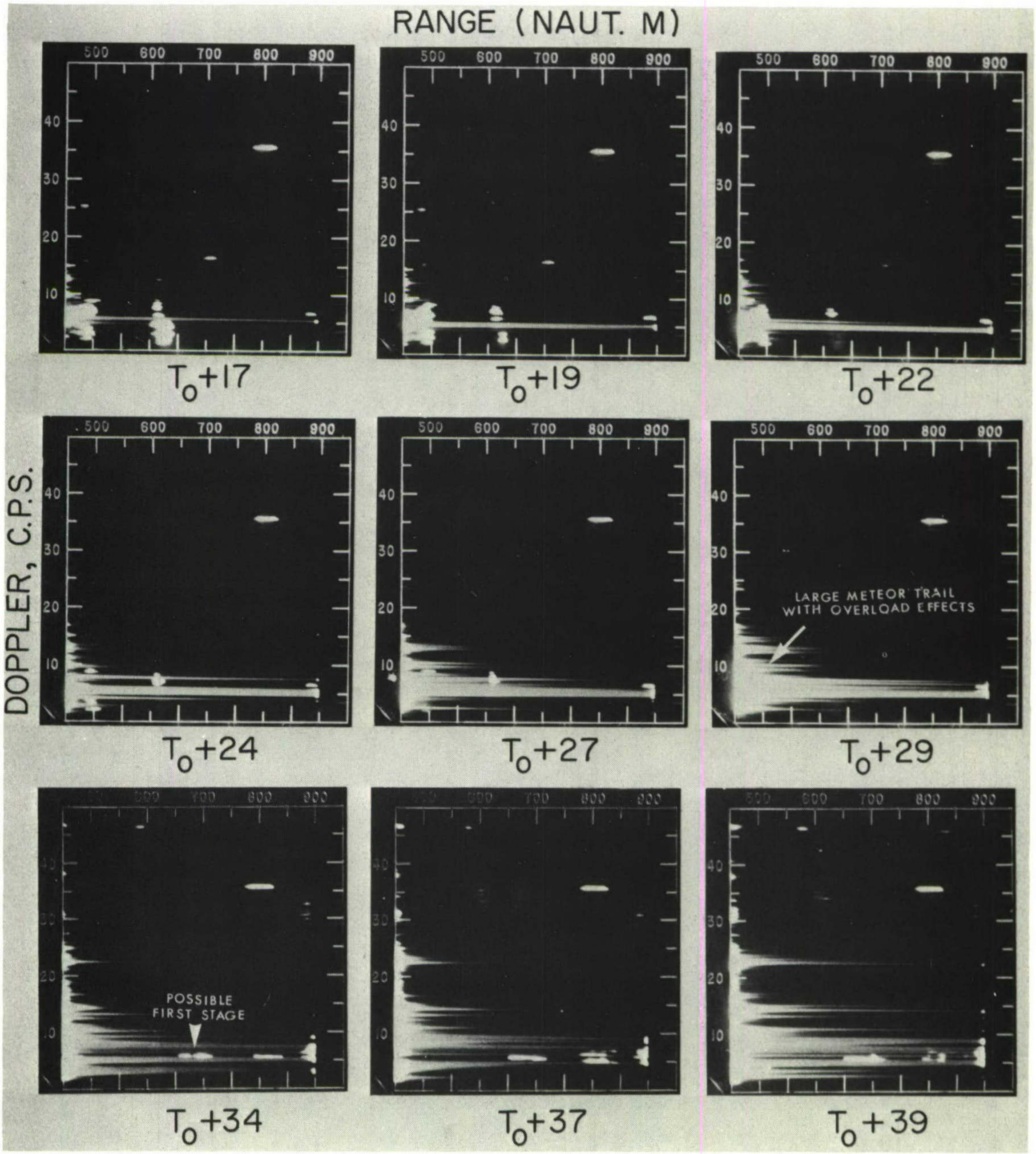


Figure A11b (Continuation of Figure A11a) - A sequence of pictures taken of the doppler versus range display. These are for observations of an A-2 Polaris launch, AMR 0238, 2/6/64, T_o 11:41:08 A.M. EST. The frequency was 19.27 Mc and a high E_s layer was used for refraction.

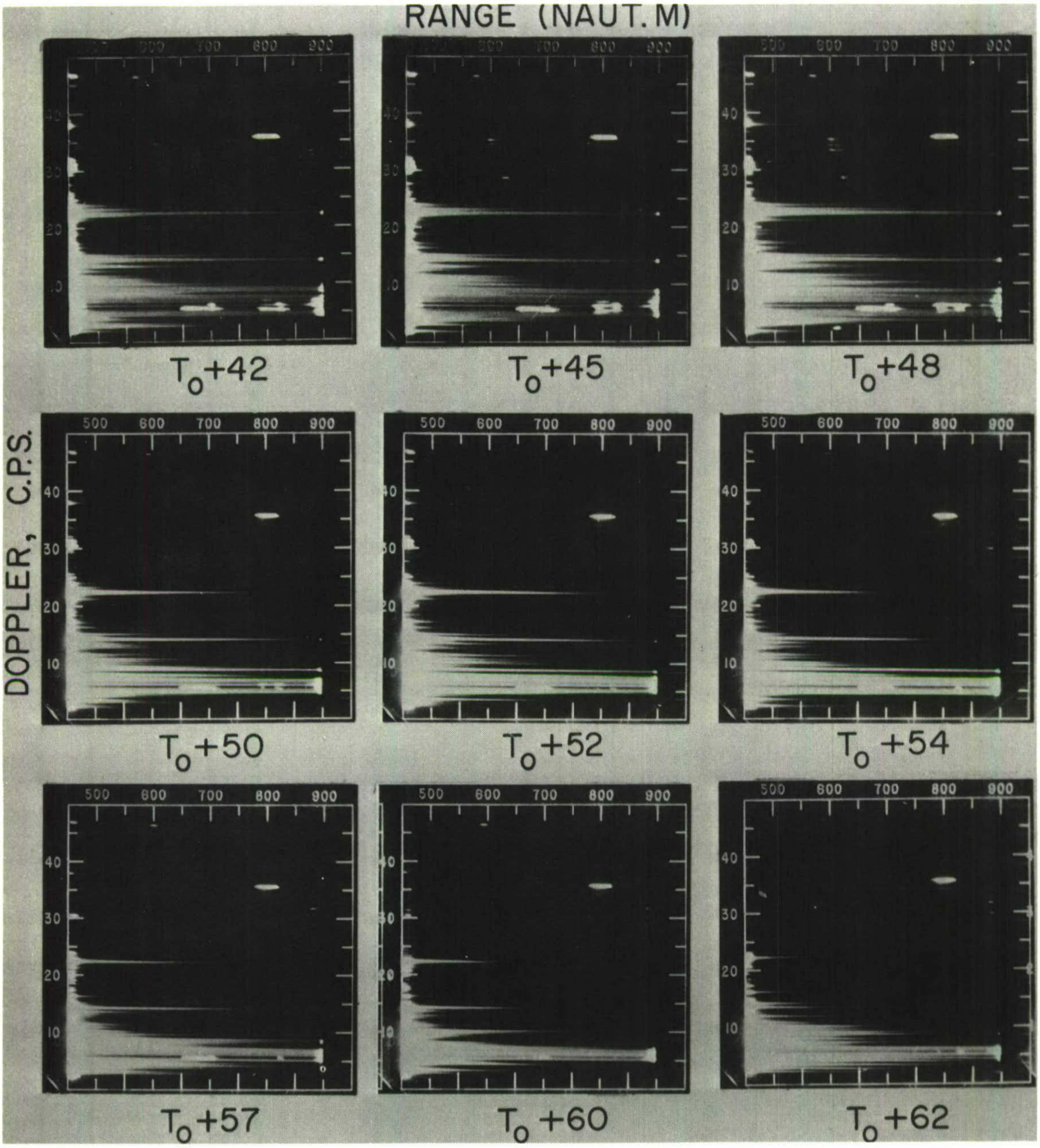


Figure A11c (Continuation of Figure A11b) - A sequence of pictures taken of the doppler versus range display. These are for observations of an A-2 Polaris launch, AMR 0238, 2/6/64, T_o 11:41:08 A.M. EST. The frequency was 19.27 Mc and a high E_s layer was used for refraction.

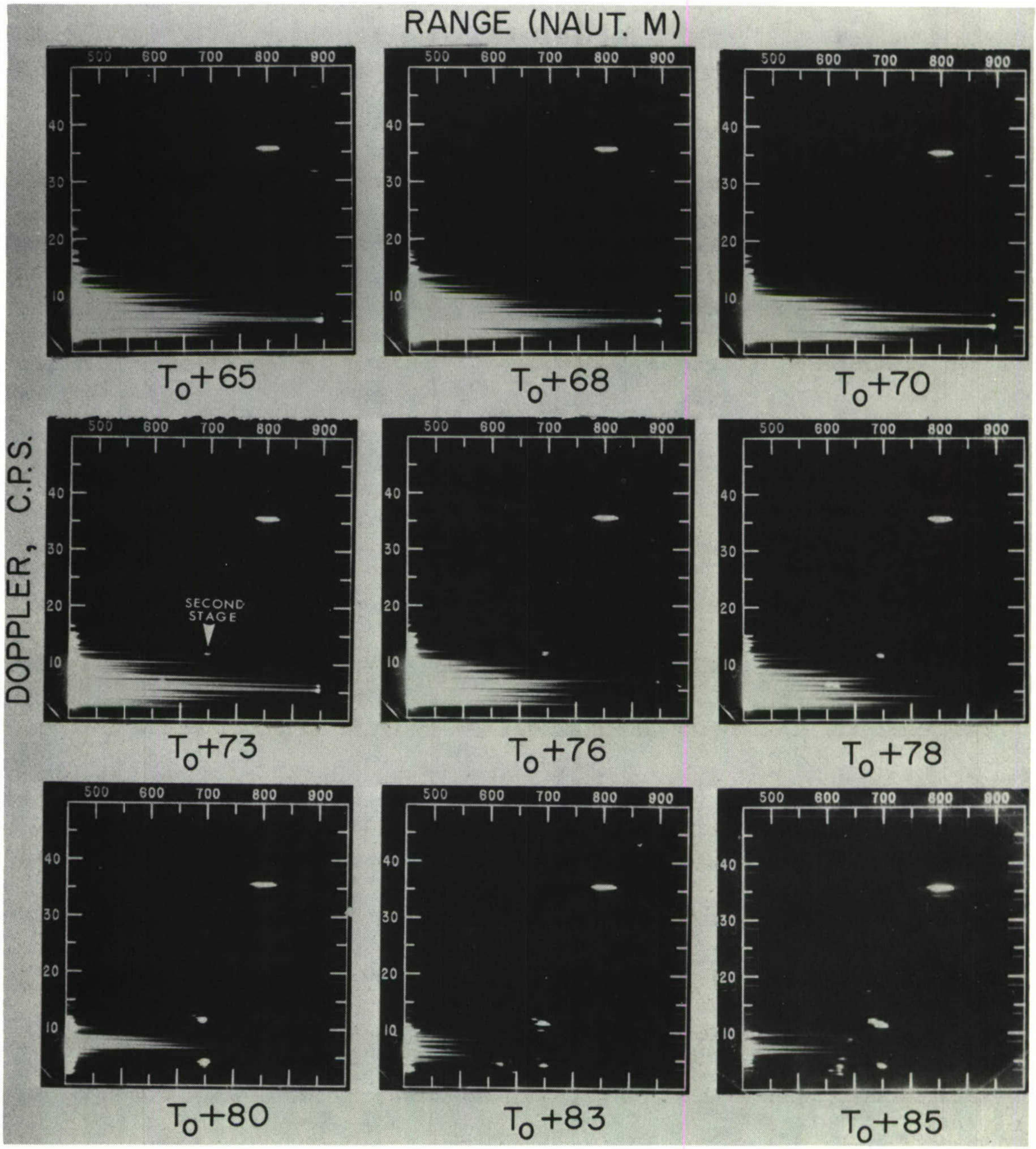


Figure A11d (Continuation of Figure A11c) - A sequence of pictures taken of the doppler versus range display. These are for observations of an A-2 Polaris launch, AMR 0238, 2/6/64, T_o 11:41:08 A.M. EST. The frequency was 19.27 Mc and a high E_s layer was used for refraction.

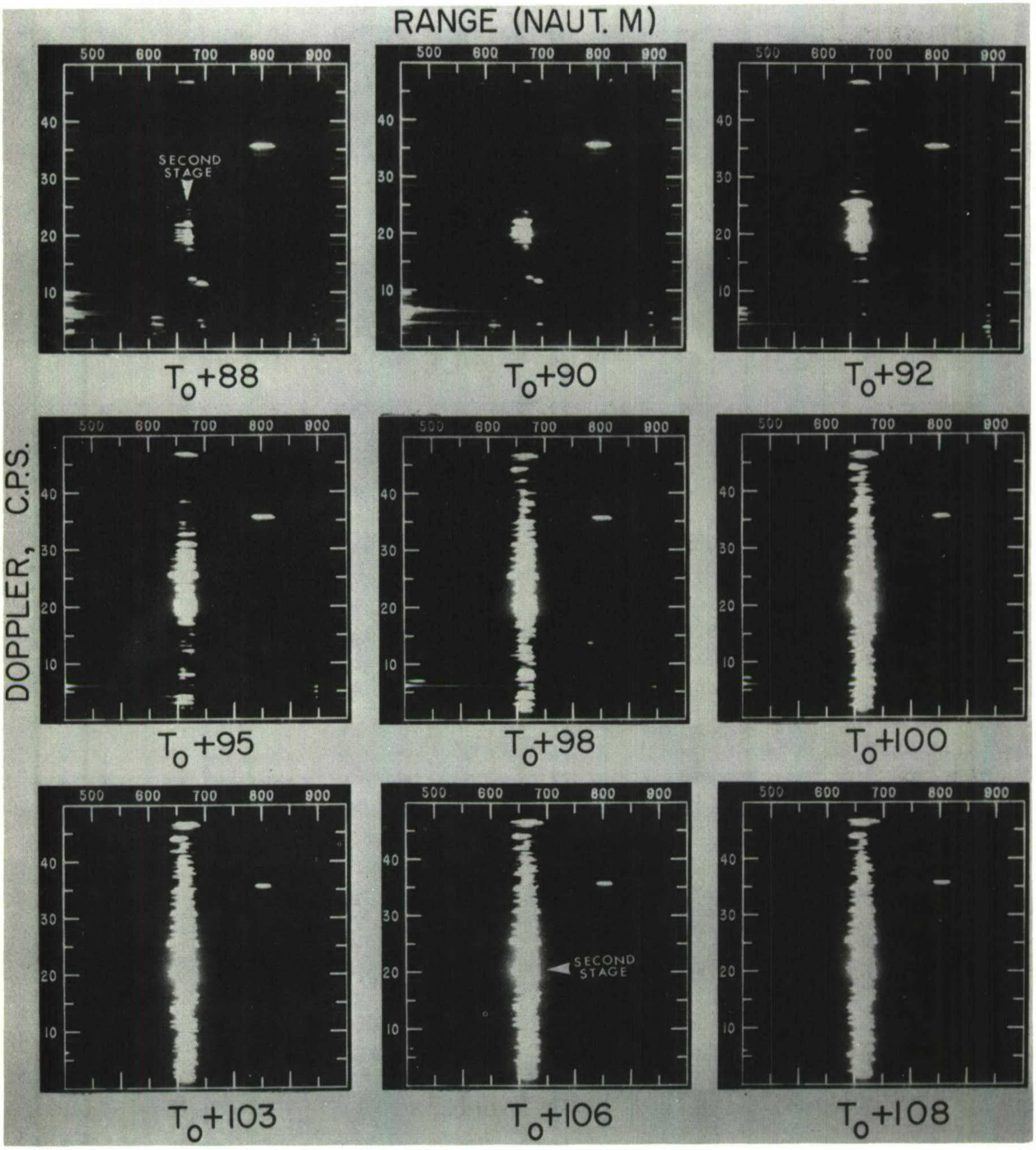


Figure A11e (Continuation of Figure A11d) - A sequence of pictures taken of the doppler versus range display. These are for observations of an A-2 Polaris launch, AMR 0238, 2/6/64, T_o 11:41:08 A.M. EST. The frequency was 19.27 Mc and a high E_s layer was used for refraction.

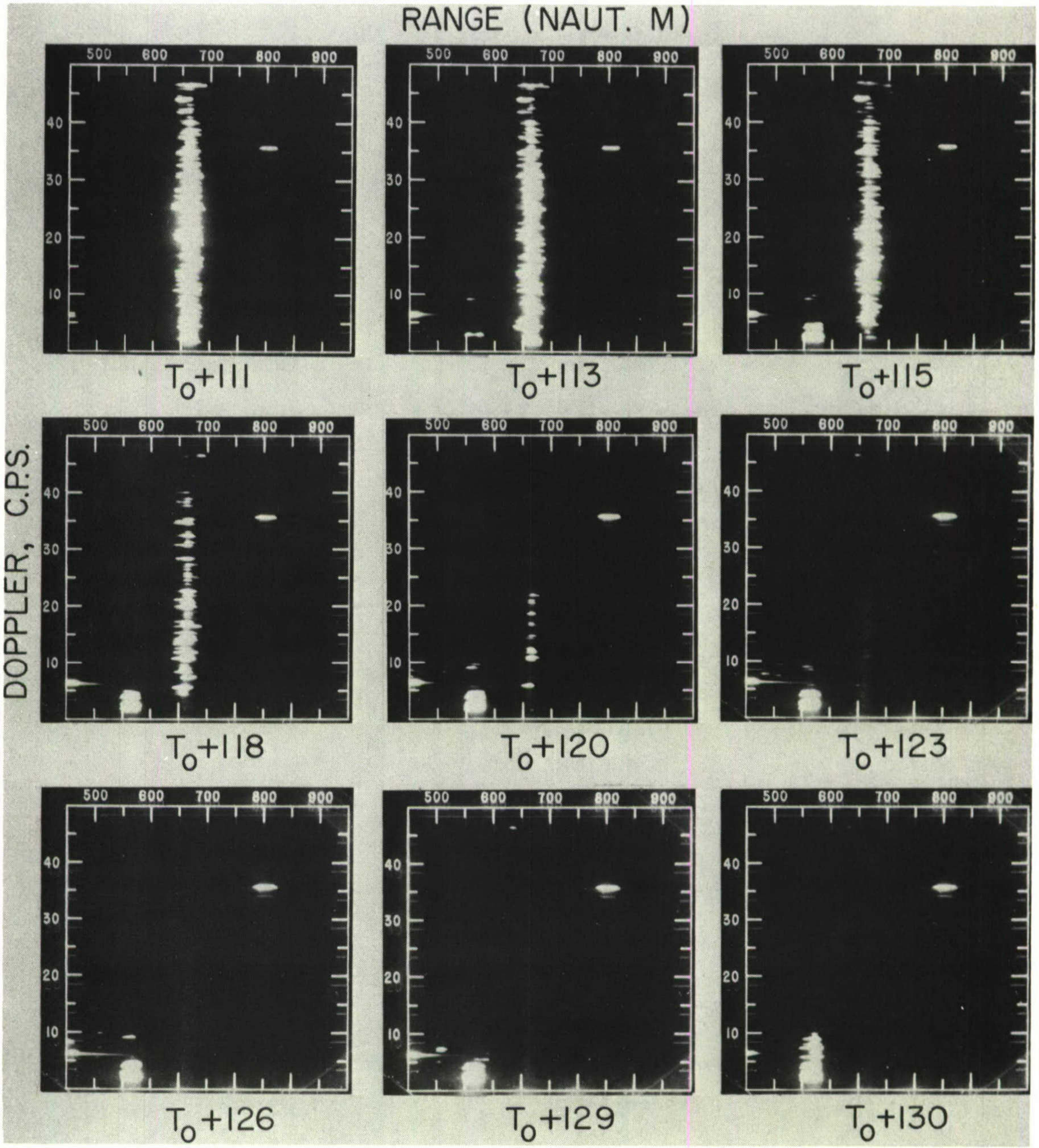


Figure A11f (Continuation of Figure A11e) - A sequence of pictures taken of the doppler versus range display. These are for observations of an A-2 Polaris launch, AMR 0238, 2/6/64, T_o 11:41:08 A.M. EST. The frequency was 19.27 Mc and a high E_s layer was used for refraction.

APPENDIX B
EXTENDED RANGE AIRCRAFT TRACKING

J. L. Ahearn, W. C. Headrick, J. M. Headrick,
C. B. Tesauro and E. N. Zettle
U. S. Naval Research Laboratory
Washington, D. C.

I. INTRODUCTION

A part of the NRL HF radar mission is to furnish feasibility and specification data for extension of radar range by using ionospheric refraction. The installation at the Chesapeake Bay Annex of the Naval Research Laboratory is a high power (NRL bibliography item 43) coherent pulse doppler system which employs earch backscatter rejection filters able to handle in excess of 70 db clutter to signal ratios (NRL bibliography item 24). After clutter filtering a zero frequency IF is sampled and stored with range segregation on a magnetic drum or disk using a packing ratio of 82,800 to 1. The past 20 seconds of signal information is continuously available for study in each 1/180 second, due to the time compression. Results described herein represent a complete doppler versus range analysis for each time period of 1.8 seconds. The resolution bandwidth is the equivalent of 1/3 cps (3,4).

In this report radar display data taken on a flight made specifically for NRL use is given. The flight took place on 29 November 1962. The aircraft was a P3V (similar to the commercial Electra), and it flew at 24,000 ft. from Lajes, Azores to Norfolk, Virginia. Radar tracking was performed between great circle ground ranges of 1978 & 1391 naut. mi. from the Chesapeake Bay Annex of NRL. Apparent aircraft echoing cross sections for this P3V are given, and the variations in apparent echoing area are discussed.

II. EXPERIMENTAL RESULTS

During the controlled P3V flight of 29 November 1962, the radar operated on 18.036 Mc with 4.6 Mw peak power, 60 kw average power, and a free space antenna gain of 19.6 db. Figure 1 shows an amplitude versus range distribution of earth backscatter during and in the direction of the flight. The higher level backscatter extends from 975 naut. mi. to about 2000 naut. mi. and this is the region in which the flight was tracked.

Figures 2 and 3 show a sequence of range-velocity-intensity display scans during the portion of the flight from about 12:18 P.M. EST to 12;32 P.M. Time after 12:15 P.M. is indicated below each frame in minutes and seconds. The ordinate indicates doppler frequency from 0 - 45 cps while the abscissa indicates approximate radar range from 1350-1800 naut. mi. Range and range-rate strobes can be used for precise target logging. The P3V return appears at coordinates (200,18) in the first frame of Fig. 2 and a calibration signal appears at (240,12).

The target moves to (90,18) in the last frame of Fig. 3. During this 14-minute period the radar range measured by the range strobe changes 80 naut. mi. This corresponds to a range rate of 343 knots. The average range rate strobe reading during the same time was 347 knots.

Figure 4 shows the P3V apparent radar cross section as the plane closed in range. The equation used to find cross section is:

$$\sigma = \frac{(4\pi)^3 R^4 Pr}{G^2 \lambda^2 Pt}$$

where

Pr and Pt are the received and transmitted powers

R is the slant range to the target

G is the one way antenna gain

This equation does not take into account any loss in the medium for the task of even roughly quantifying losses in the medium of over-the-horizon detections is far from simple. Computed cross section values are lower than those which would result if the medium loss factor were included. The dashed portions of Fig. 4 indicate times when the radar was inoperative. Received signal amplitudes are taken every minute; in 10 cases the echo was not present at the reading time. These correspond to zero cross section and are carried as such in computing average and median values. The zero values are plotted on Fig. 4 along the base line which corresponds to a cross section of 10 square meters. The median value for the radar cross section is 370 square meters and the average is 760 square meters. In computing, the maximum available antenna gain of 25.6 db is used. That is, 6 db is added to the free space gain of 19,6 db to account for placement of the antenna over ground. There will be times when the target energy doesn't come into the antenna on the nose of a lobe and again the computed target cross section will be lower than if the actual antenna gain were used.

Figure 5 shows a doppler time history of a six minute portion of this P3V flight when the plane was in the 1570 naut. mi. slant range region. For this type of presentation the incoming signals are range gated with a 300 μsec gate which moves with the target. Time in minutes runs along the abscissa and range rate in knots runs along the ordinate. The aircraft doppler track appears as a broken line. This technique allows one to observe the target situation from minutes in the past until the present time. In this respect it gives a doppler time history.

Figure 6 gives a comparison between plane over-the-ground range to CBA as reported by the navigator and slant range taken from the radar display. The slant range is about 70 naut. mi. greater than great circle ground range for this distance and ionosphere. The difference between slant range and ground range can be estimated roughly with data such as given in Fig. 1 and precisely with complete knowledge of the prevailing ionosphere.

The P3V data given above was taken on a transatlantic path and at times when few other targets were present. It is of interest to show a radar display of an area containing a greater aircraft population. Figure 7 shows aircraft returns on the radar doppler-range display when looking into the interior of the USA. This observation was a by-product of a setup for the observation of a West Coast missile launch and was made with a smaller gain antenna. Other operating parameters were as follows:

Operating frequency 18.036 Mc
Antenna bearing 279° (i.e., looking west from NRL-CBA)
Antenna 3 db beamwidth 30°, free space gain 11.6 db
Power output 100 kw average
PRF 90
1st hop backscatter 1000 naut. mi. - 1950 naut. mi.
Date 12/13/63 3:35 P.M. EST

The receiver was gated on for the range intervals 450-900, 1350-1800, 2250-2700, etc., naut. mi. The backscatter conditions indicated that the observed returns could only come from the 1350-1800 naut. mi. range. The figure shows doppler frequency along the ordinate 0-45 cps and range 1350-1800 naut. mi. along the abscissa. The large signal at 30 cps and 1700 naut. mi. is a calibration signal which corresponds to a 10 μv p to p signal at the antenna terminals. A target giving the same signal strength at this range would have a cross section of 1.156×10^4 square meters for an antenna gain 6 db above the 11.6 db free space gain. There are at least nine aircraft echoes in this viewed area which lies west of Denver, Colorado, and extends from Helena, Montana, in the north to White Sands, N. M. in the south. Thus Fig. 7 represents a 20-second marginal power density look at the area outlined.

III. DISCUSSION OF APPARENT ECHOING CROSS SECTION

A discussion of transmission medium effects upon apparent echoing cross section may be helpful in studying the aircraft detection problem. Three idealized cases will be treated.

Case I: Consider an antenna and a target in free space with the antenna being used for both transmitting and receiving. The power density at the target is $S_t = \frac{PoGo}{4\pi R^2}$ where Po is the power into the antenna, Go is the free space gain of the antenna, and R is the range to the target. The power density at the antenna due to the echo from the target is $Sr = \frac{S_t \sigma}{4\pi R^2}$ where σ is the target echoing cross section. The cross section for the free space condition will be used to define $\sigma_o = \frac{4\pi R^2 S_r}{S_t}$.

Since $S_r = \frac{P_r}{A}$ where P_r is power available for the receiver and $A = \frac{G_o \lambda^2}{4}$ is the capture area of the antenna with λ being the wavelength,

$$\sigma_o = \frac{4\pi R^2 S_r}{S_t} = \frac{P_r (4\pi)^3 R^4}{P_o G_o^2 \lambda^2}.$$

Case II: For this case the same antenna and target are placed over a conducting surface. The antenna orientation is such that maximum gain is parallel to the surface. In Fig. 8 radiation from the antenna at A can reach the target at P by the path AP and by path ABP. Assuming that no loss occurs from the reflection at B and that ABP - AP $\ll$ AP, the electric field at P will be twice the free space value, E_o, when the electrical path length ABP differs from AP by $n\lambda$ and will be zero when the path length difference is $(n + \frac{1}{2})\lambda$. As the elevation angle is increased from zero to 90°, the number of maxima where the field is $2E_o$ is $\frac{2h}{\lambda}$. Since power is proportional to E^2, the maximum power density at P is $S \propto (2E_o)^2$ or four times the free space value. Applying the same argument to the echo paths from the target to the receiver gives another increase in power by a factor of four. Thus to calculate σ_o, $4G_o$ would be used in the place of G_o when P is at a point of maximum field.

Case III: In this case the target is placed over-the-horizon and is illuminated via the ionosphere. Figure 9 shows the target illuminated by four different paths and if the four are in phase, $S_t \propto (4E_o)^2 = 16E_o^2$. On the return to the receiving antenna another increase of 16 with respect to the free space case would be realized. To calculate σ_o in an idealized lossless situation where the radiation arrived at the target in phase, $16G_o$ would be used in the place of G_o.

The NRL antenna used in tracking aircraft over-the-horizon has a comparatively narrow beamwidth in the horizontal plane but has free space directivity in the vertical plane of 12.5° to 25° between the 3 db points over the design frequency range. The antenna height of 166 feet gives a fairly small number of lobes in the vertical plane. The lowest two lobes are probably 4° wide between their 3 db points; yet they illuminate a ground range hundreds of miles in extent via the ionosphere.

A different situation exists at the target end of the over-the-horizon path. Here the target is usually thousands of feet above the earth's surfact and lobe structure due to target height above the earth is quite extensive. For example, at an operating frequency of 18.036 mc/s an aircraft flying at 24,000 feet would give 880 lobes in the vertical plane. With a moderately fast aircraft, target returns could easily go through maxima and minima at the rate of one per minute. Effective cross sections computed from over-the-horizon aircraft echo amplitudes can vary due to this cause alone from zero to 24 db greater than σ_o.

Using a simplified model, i.e., considering only spreading loss and four ideal type paths, Figs. 10 and 11 show how the power received from an over-the-horizon target will vary as a function of over-the-ground target range for the four-path case. The reference is a hypothetical single free space path which does not involve any ground or ionospheric reflection. These computations were made using a G-15 computer. Target heights of 1 kilofeet and 24 kilofeet are indicated. The height factor affects the time it takes a moving target to go through a maximum and minimum cycle, while the frequency of operation determines the placement of the maxima. Table I shows the time for the returns from a 400-knot target to go from a maximum value to the next maximum value.

TARGET

Altitude KF	Over-the-ground speed (knots)	Max. to max. time (Min.)
1	400	21
24	400	1

TABLE I

The target is on a great circle course which passes over the radar site.

In real life the ionosphere does not reflect exactly like a perfect mirror. This difference from the ideal case treated above tends to apply smoothing to the signal peaks and nulls, and at times even introduces additional peaks and nulls. However, the results shown in Figs. 9 and 10 and Table I illustrate a difference between low-altitude and high-altitude detection requirements. That is, a longer period of surveillance is required in the detection of extremely low altitude targets (flying at 100 feet or so), particularly under typical nighttime propagation conditions when the frequency of operation might be as low as 5 mc/s. This period can be shortened substantially, however, when (under normal daytime conditions) operation in the 15-20 mc/s region is possible and frequency agility is utilized.

IV. COMMENTS

In this report, the results of tracking one transatlantic P3V flight have been treated in some detail. One HF frequency, 18.036 Mc, was used to obtain adequate coverage of the interval between 1000 and 2000 naut. mi. distance from the radar. The P3V was almost continuously tracked for the distance between 1475 and 2000 naut. mi. except for two periods when the radar was not operating. After the aircraft closed to 1475 naut. mi., tracking was terminated due to demand for a different radar use; continued observation was possible in to about 1000 naut. mi. This example is illustrative of what can be done with a HF extended range radar.

An important feature of HF over-the-horizon radars is that aircraft targets can be detected at any altitude so long as they have sufficient relative velocity. The fading pattern of targets is dependent upon altitude to some extent with the faster fade rates being associated with higher target altitudes.

Thousands of real-time over-the-horizon aircraft detections have been made with the NRL radar in the 500 to 2000 naut. mi. interval. In hundreds of cases a study of aircraft echo has been made by tracking for some distance and recording received signal amplitudes (NRL bibliography items 35, 40 and 41). The aircraft have ranged from the F100 (38 ft. wing span and 47 ft. length) to the KC-135 in size and have included piston and turbo-prop types. Exclusive of times of ionospheric disturbance or storm, and when the required operating frequency was outside the capability of this experimental radar, fair illumination of a portion of the distance between 500 and 2000 naut. mi. has been always possible. Following are the essential features of the radar:

1. One way antenna gain of approximately 20 db
2. Radiated power of 60 to 100 kw average, 4.6 Mw peak
3. In excess of 70 db rejection of earth backscatter
4. One third cycle per second bandwidth predetection signal filter

It is felt that sufficient experience has been accumulated to estimate system requirements for one hop over-the-horizon aircraft detection. Principal deficiencies in knowledge are due to limited experience (three years) and no use of frequencies below 13.5 mc.

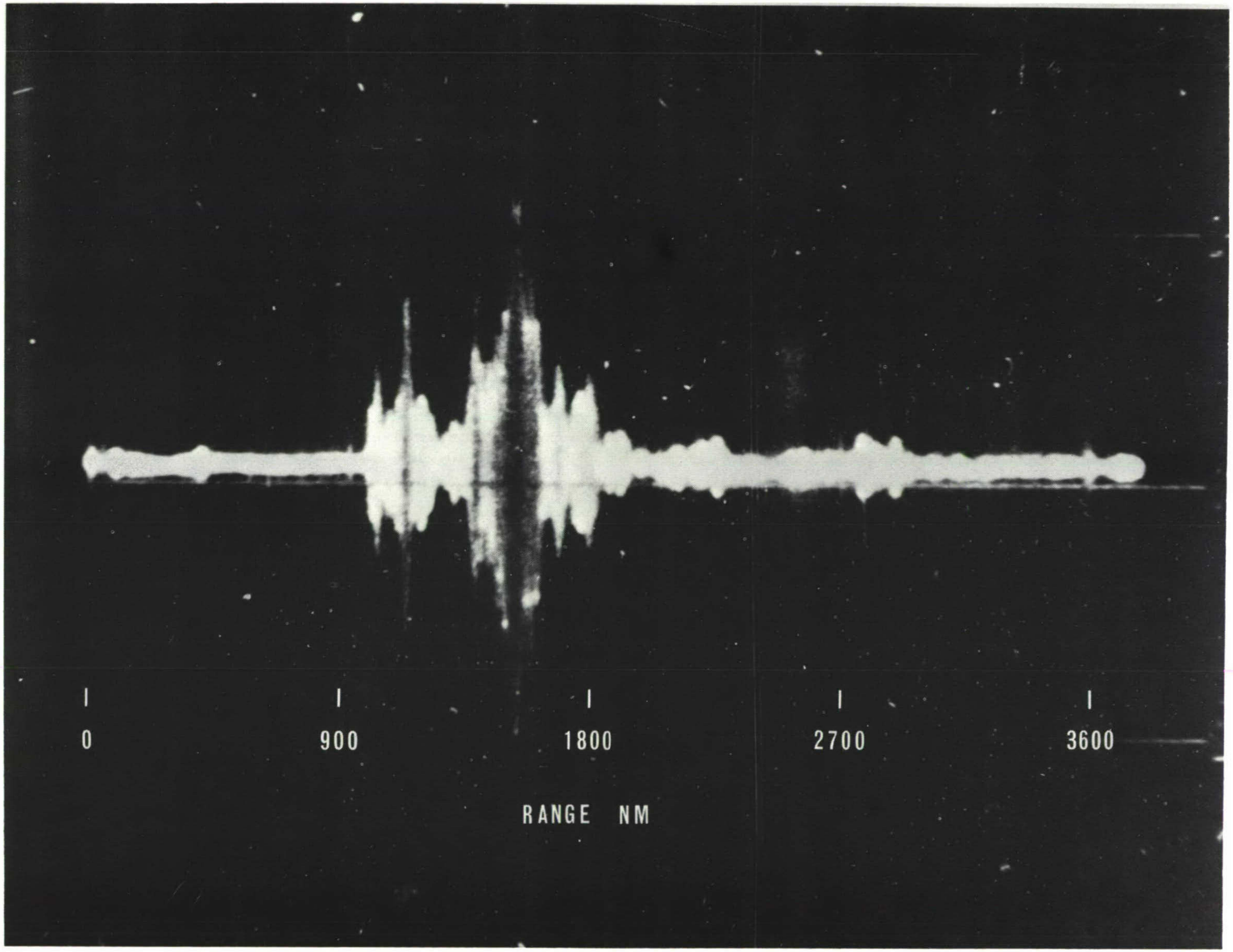


Figure B1 - Backscatter during P3V flight

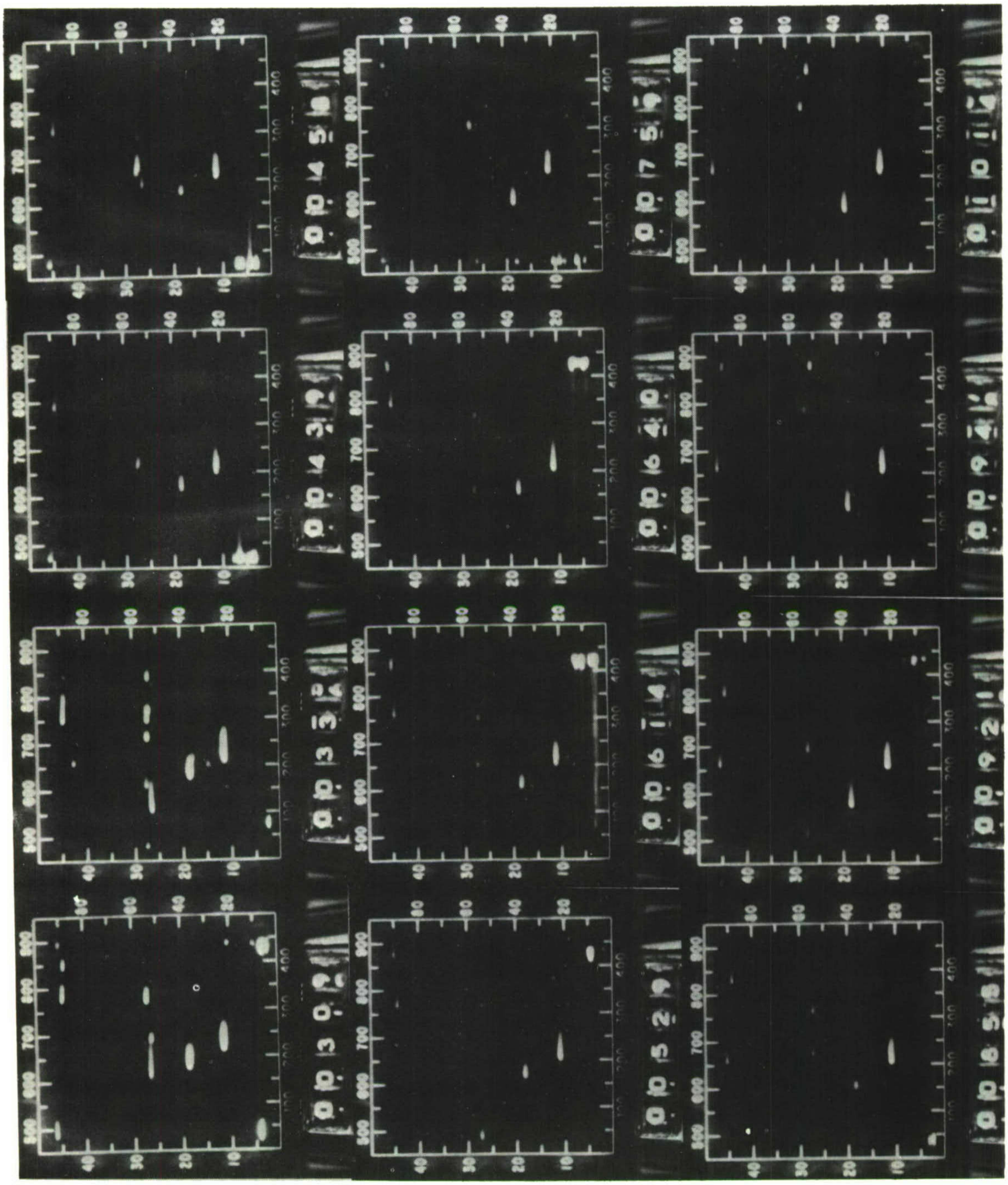


Figure B2 - Primary display - P3V flight - 12:18:09 to 12:25:14 P.M. EST.

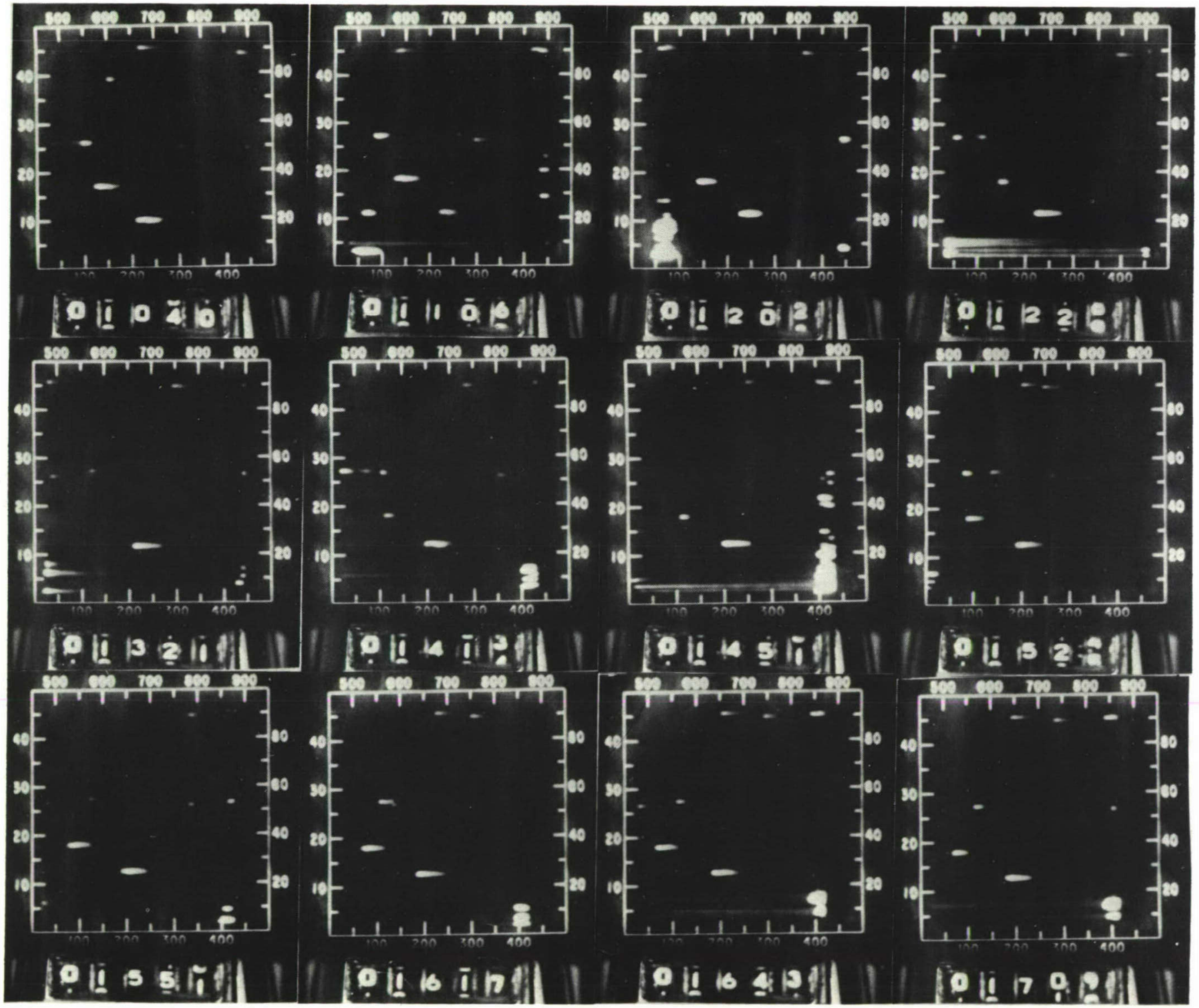


Figure B3 - Primary display - P3V flight - 12:25:40 to 12:32:09 P.M. EST.

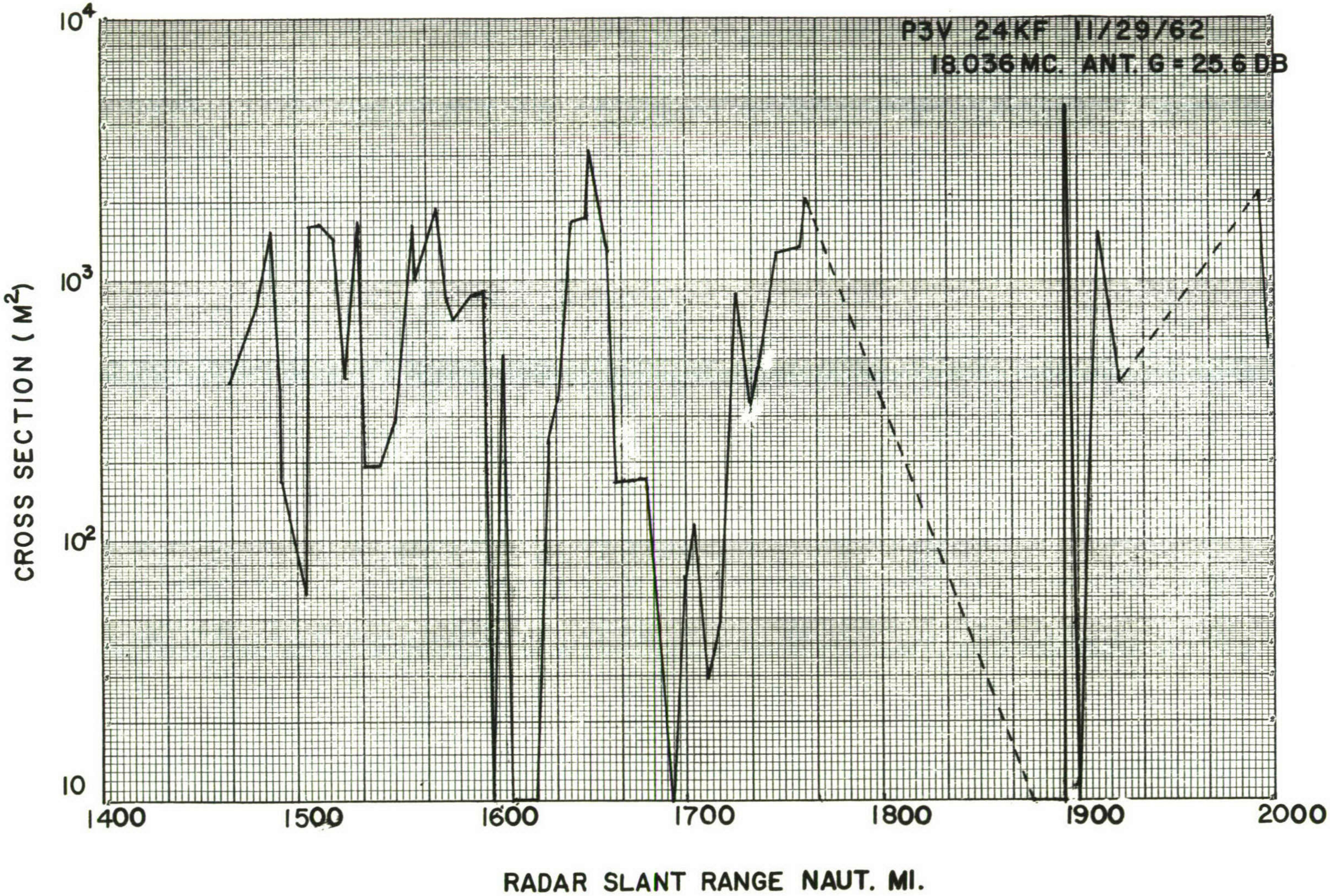


Figure B4 - Apparent radar cross section as a function of slant range.

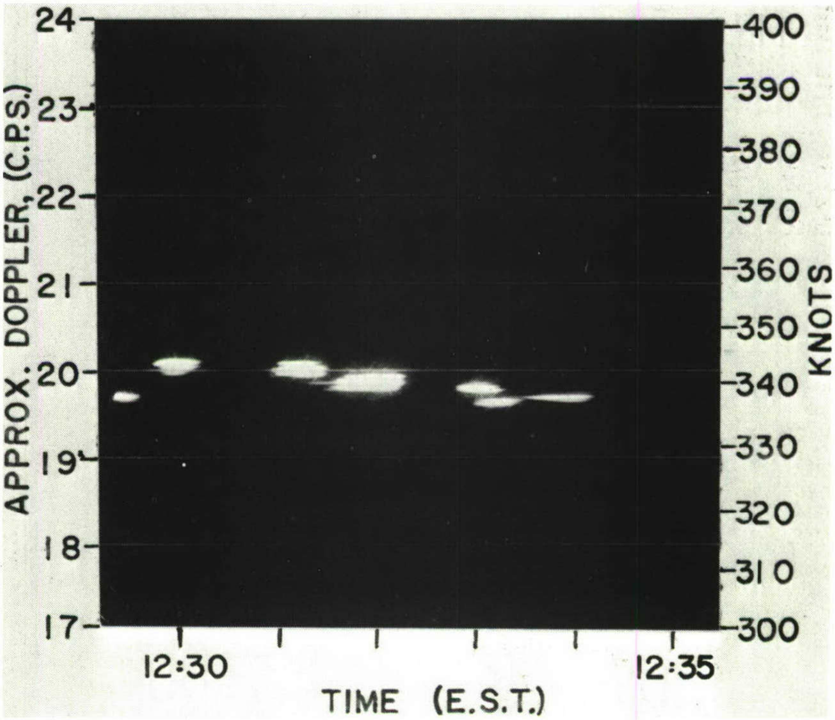


Figure B5 - Doppler time history.

[redacted]

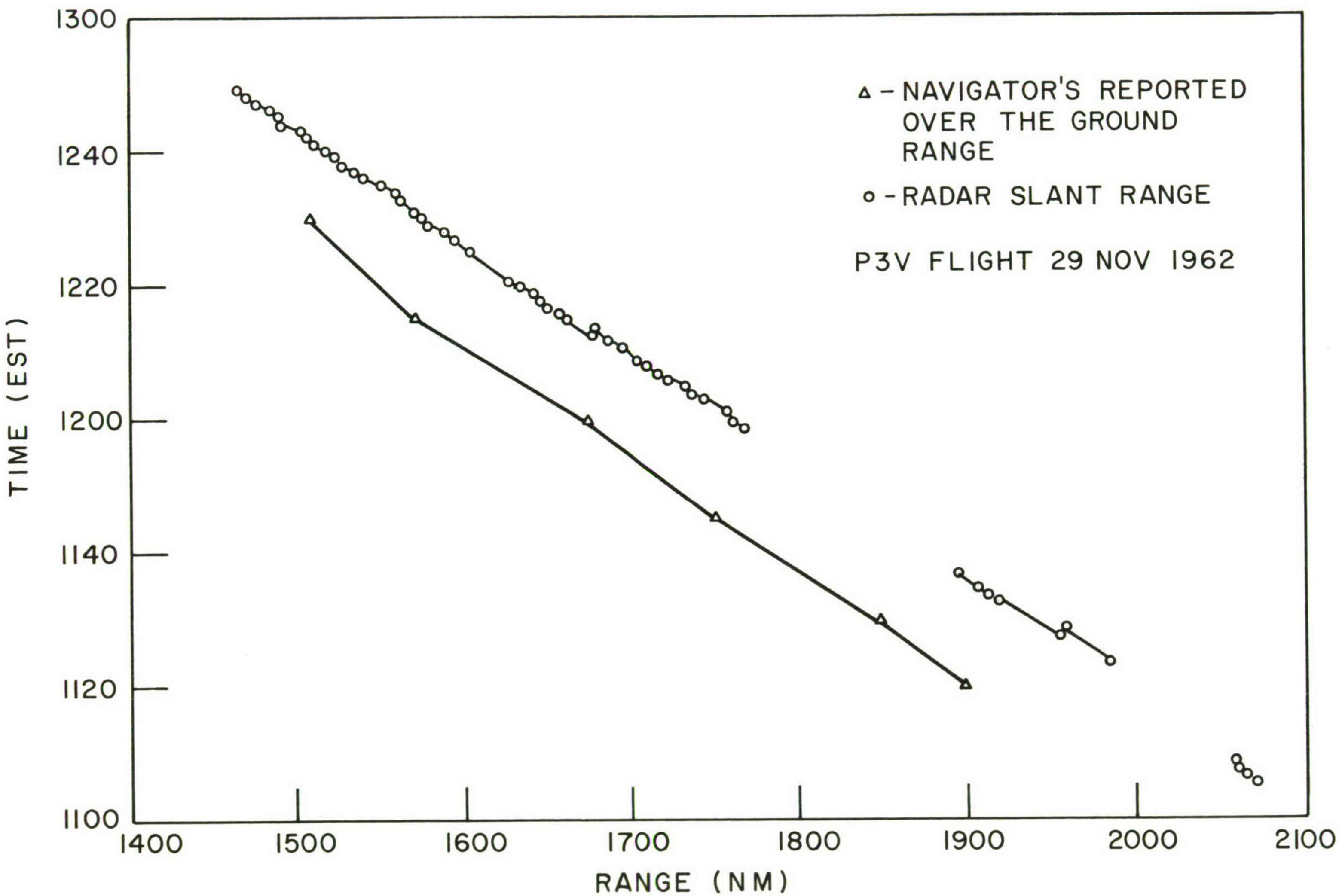


Figure B6 - Navigator over the ground range and radar slant range for P3V flight

[redacted]

[redacted]

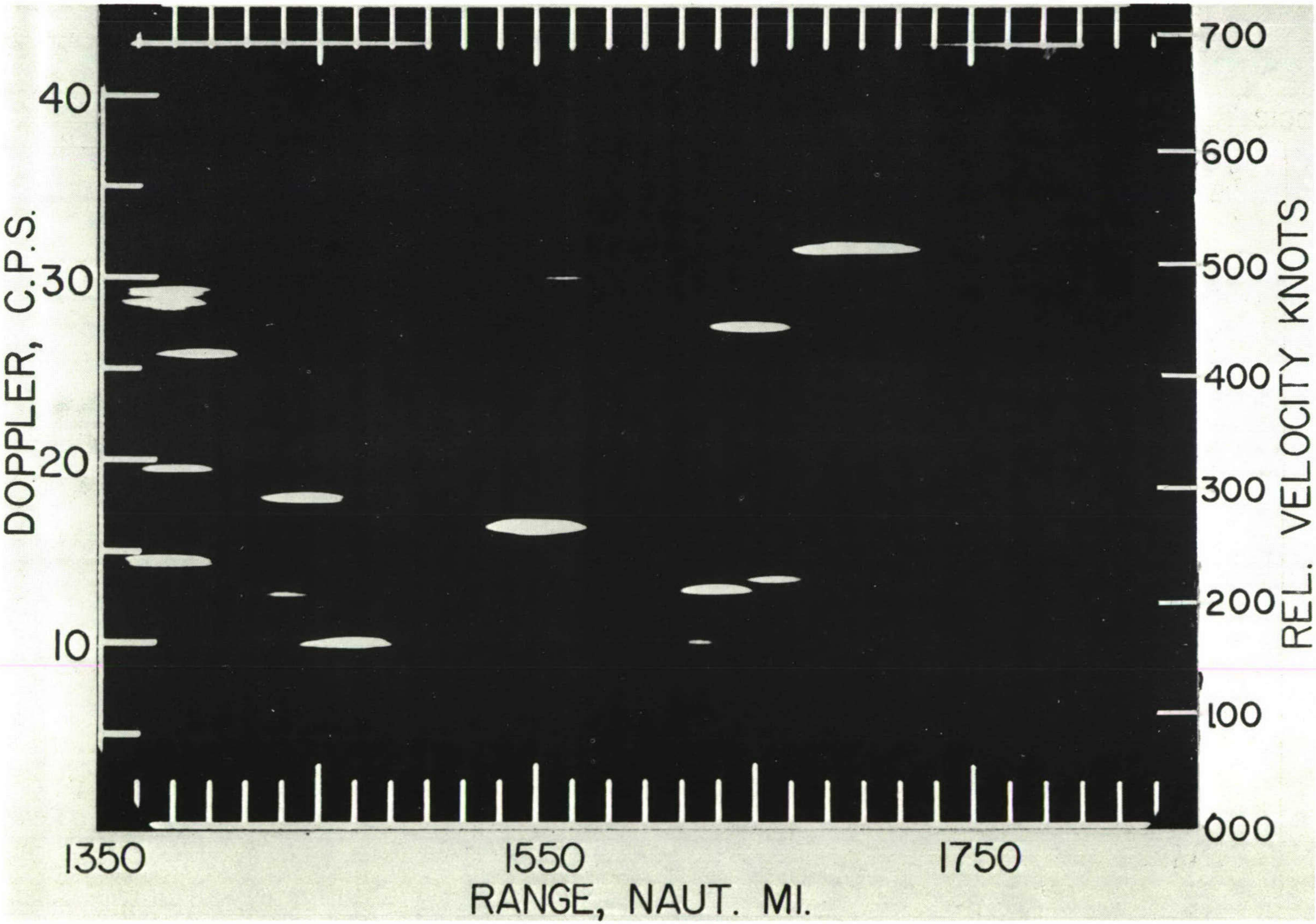


Figure B7 - Range rate or doppler versus range display of interval between 1350 and 1800 naut. mi. west of NRL - CBA. A number of aircraft returns can be seen.

[redacted]

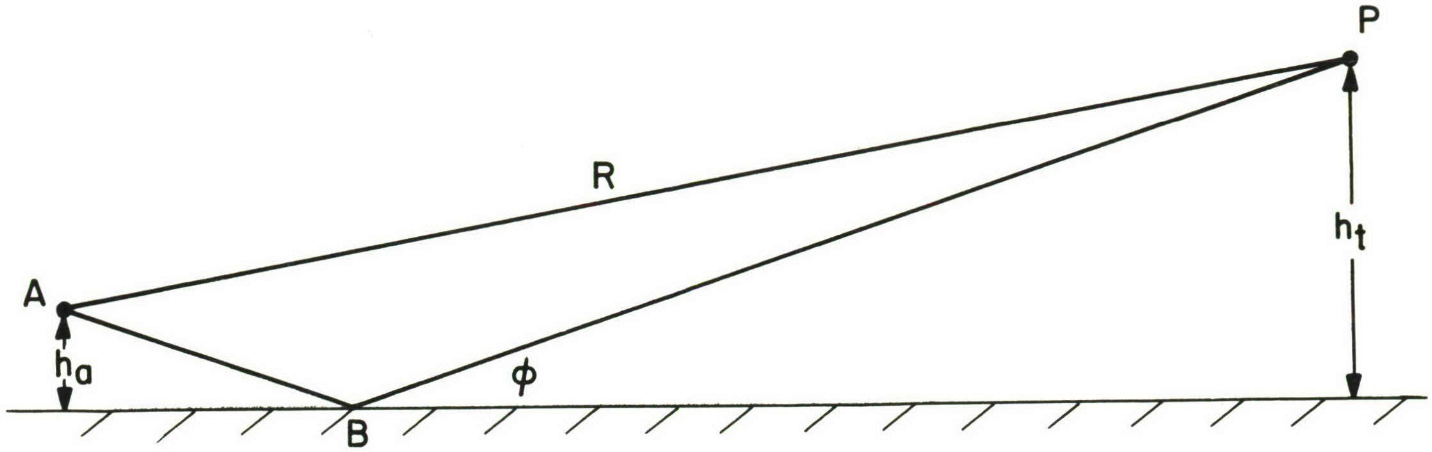


Figure B8 - Two paths between the antenna, A, and target, P, sketched for the line of sight case

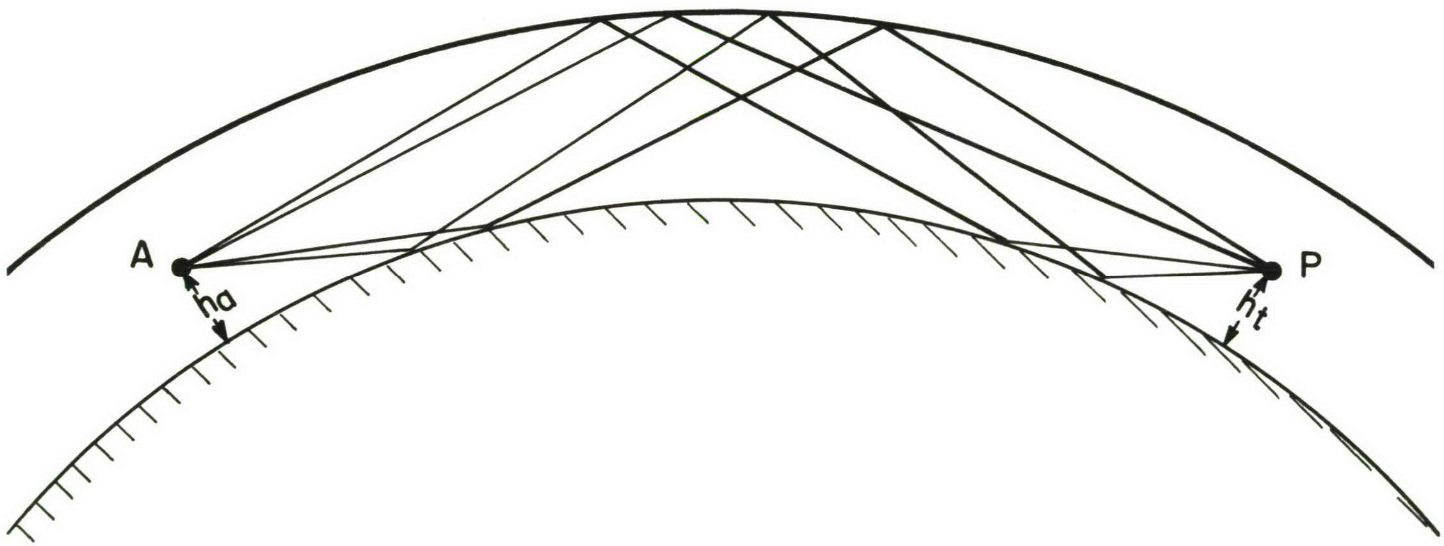


Figure B9 - The four paths between the antenna, A, and target, P, sketched for the over the horizon case.

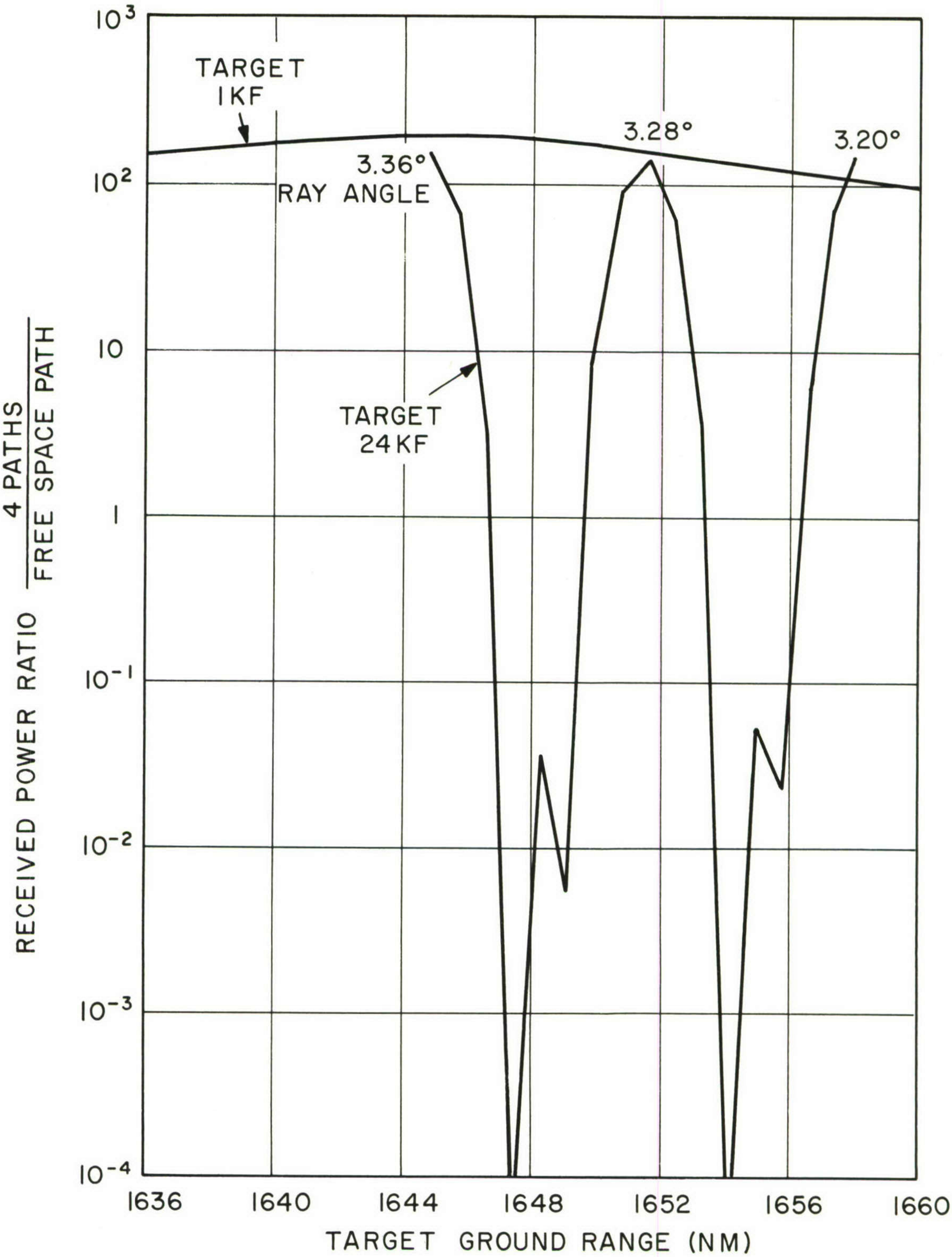


Figure B10 - Received power ratio as a function of target over the ground range. Target height 24 KF and 1 KF; transmitting antenna height 160 ft, ionospheric height 300 KM.

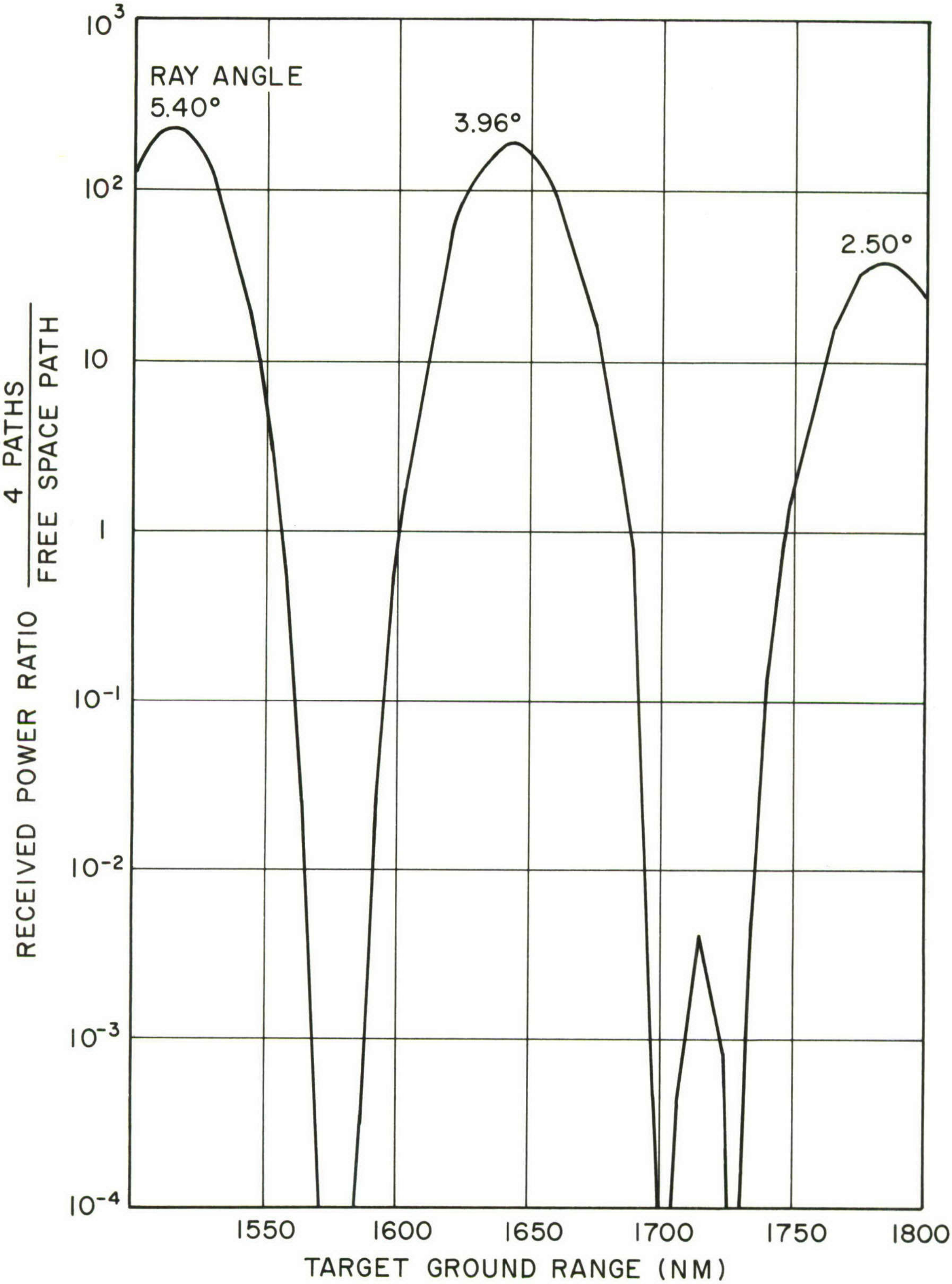


Figure B11 - Received power ratio as a function of target over the ground range. Target height 1 KF; transmitting antenna height 160 ft, ionospheric height 300 KM.

APPENDIX C
POLARIS DETECTIONS

J. M. Headrick, F. H. Utley
W. C. Headrick, J. L. Ahearn,
and E. W. Ward
U. S. Naval Research Laboratory
Washington, D. C.

I. INTRODUCTION

Considering HF detection methods, the A-2 Polaris has several features that render it more difficult to detect during the launch phase than Atlas, Titan, or Minuteman vehicles. Two of these are:

1. Skin-echoing area is small, and
2. Thrust terminates at about E-layer heights with the consequences that there are no sustained large target or perturbations presented during transit of the ionosphere.

There are at least two factors that aid in detection below the E-layer. These are:

1. Exhaust ionization is high
2. Velocity is high

The HF radar located at the NRL Chesapeake Bay Annex has been used to observe a number of Polaris launches. The radar is a coherent pulse doppler system. It uses backscatter rejection filters, range gating with short samples, and storage with packing in the signal processor. The packing with a time compression ratio of about 82,800 permits narrow-band spectrum analysis readout and display in essentially real time. Transmitter power is nominally 100 kw average and the free space antenna gain is between 10½ and 12 db for data given herein.

II. DOPPLER HISTORY FORMS

Examples of doppler versus time behavior of a Polaris from the radar's point of view is sketched in Fig. 1. An operating frequency of 19 Mc, a distance of 650 naut. mi., a reflecting layer of 140 km, and two launch directions have been assumed. The dashed curve is for a missile aimed nominally in the direction of the radar. The solid curve is for a launch going away but nearly broadside to the radar's view. A repetition rate of 90 pps has been chosen and the consequent frequency folds every 45 cps are shown for the dashed curve - of course the true doppler is always increasing for the times shown. It can be noted that for near broadside cases, truly early detection may be difficult due to backscatter rejection filter action.

III. AMR TEST 0238

Test 0238 of 3 February 1964 (T_0 = 16:4108Z), a submarine-launched A-2 Polaris, yielded good quantitative signal amplitude measurements. A frequency of 19.27 Mc was chosen principally on an interference quietness basis. Backscatter distribution prior to the test indicated good illumination from the launch site and on out by what was considered to be E_s layer refraction. Some 30 minutes after the test the backscatter distribution was again studied and the illumination at the launch site had become poor. Therefore some uncertainty exists as to how well energy was placed upon the missile track. A plan presentation of the missile track and radar view is shown in Fig. 2. Look azimuthal angles are near broadside during the thrust phase. Figure 3 shows illumination in the vertical planes that include the radar and the missile. The vertical antenna pattern is indicated including interference due to the earth. The missile track is viewed via the second lobe at T_0 and via the first lobe at burnout for a reflecting layer height of 140 km. In Fig. 4a, relative doppler on the vertical scale versus time in seconds after lift-off on the horizontal scale is given assuming reflection from three ionospheric heights, 115, 135, and 140 km. Computations were made using preflight trajectory data, which is probably adequate for the purpose. The doppler-time plot is interpreted to show first an approach doppler, zero doppler around 60 sec, and recede doppler thereafter. The 90-pps repetition rate causes a foldback at 45 cps which is indicated (actual missile doppler continues to increase). Figure 4b shows the real time doppler-intensity-time readout to the same scale as Fig. 4a; the similarity is evident, the returns between 80 and 110 sec being unmistakable. Figure 4c is a later analysis and readout where the sensitivity was increased by at least 10 db for times between 60 and 80 sec and probably shows additional returns plus some post-staging splashes. The slowly changing doppler line at about 7 cps between 20 and 60 sec appears to be the first stage; identification is not considered positive. Figure 5 is a picture taken of the doppler-time display 7 minutes after launch; this is intended to give an idea as to how this signature stands out against the background.

Between 75 and 110 seconds the echoes from the burning second stage were of sufficient amplitude for good measurement. The technique employed was as follows:

1. Display the clutter-filtered zero frequency i-f or bi-polar video on an A-scope
2. Take 5-second time exposures of the trace
3. Measure the greatest amplitude of the echo signal
4. Inject a calibrated simulated signal on the antenna line at similar levels to that of the echo and take 5-second exposure pictures
5. Effect with comparison a signal amplitude determination

Using the signal amplitude determination, echoing cross sections were computed with the following relation:

$$\sigma = \frac{P_r}{P_o} \frac{(4\pi)^3}{G_o^2 \lambda^2} R^4,$$

that is, the simple radar range equation. The antenna gain G_o, was taken to be the theoretical free space gain of 12 db + 6 db due to the ground giving a total of 18 db. No path losses were included. The other necessary values used were a range of 655 when given in naut. mi. and transmitted peak power of 4.6 Mw. Results are given below in tabular form. For the three highest signal levels, system linearity was exceeded and the cross sections are at least as big as given but not an order of magnitude larger.

Time Interval, Sec.	Peak to peak sign. on antenna terminals μv	σ m^2	H km	Absolute Velocity kf/s
70-75	20	9.15×10^2	55	7.26
75-80	25	1.43×10^3		
80-85	13	3.87×10^2	71	9.3
85-90	40	3.66×10^3		
90-95	200	9.15×10^4	91	11.9
95-100	500	6.72×10^5		
100-105	200	9.15×10^4	115	13.4
105-110	30	2.06×10^3		

In Fig. 6 the echoing cross section, σ, is plotted against time after lift off. Relative antenna gain (assuming reflection from a 135 km ionosphere) is sketched in at the bottom and the pertinent readings are seen to have occurred in the region of the first interference maximum. An additional parameter, A, the rocket exhaust plume area is plotted. This area was determined by expanding the exhaust gas to ambient pressure (ARDC) by the simple relation

$$\text{Area plume} = \frac{(\text{Area throat}) \times (\text{Pressure throat})}{(\text{Ambient pressure})}$$

The effective exhaust length is probably 10 to 20 times the diameter corresponding to a circle of the area computed, and thus if it is a perfect reflector would have a radar cross section somewhat larger than the parameter A. The nature of the plume can be speculated upon further. To a first approximation the Polaris A-2 second stage exhaust can be considered to start with 10^{14} electrons/cc at the rocket throat. If the expansion is considered with the electron population frozen, some 10^9 electrons/cc exist at 100 km. While the parameter plotted as A in Fig. 6 should not be relied upon literally as indicating absolute size of target it does suggest that the exhaust does provide a target.

IV. OTHER A-2 SIGNATURES

Figures 7 through 13 are doppler histories obtained on some other similar missile tests. Radar operation was similar to that for Test 0238 except that lower rf frequencies were employed. In all these cases noise levels and/or distracting meteor trail echoes worsened conditions; a lower reflecting height existed; and these factors probably are the reason that no identifiable first stage echoes can be demonstrated. However, the second echoes are quite similar 1 to those of Test 0238. In Figs. 11, 12, and 13, readouts on Test 3797 are shown for three range gate positions. This is interesting because two identifiable peak signal strengths coincide with the range gate positions of Fig. 11 (665 naut. mi.) and Fig. 12 (730 naut. mi.). This is the only time such phenomena have been noted when using the E_s layer. For the range gate position of Fig. 13 (750 naut. mi.) the missile echo is diminishing in amplitude but a nice aircraft track is shown.

V. DISCUSSION

An interesting feature in all of these tests is the abrupt increase in echo strength starting somewhere between 70 and 85 seconds. Careful examination with a higher time resolution analysis than has been displayed in this paper reveals in each case a discernible, weaker, velocity line echo preceding and contiguous with the larger echo displayed in Figs. 5 and 7 through 11. There are a number of factors that inhibit interpretation, chief of these being the nearness of an antenna pattern null and the radar system zero velocity null. However, it is believed that the earlier and weaker echoes are from the exhaust ionization and that the abrupt increase in size is due to an environment reaction to the missile and its exhaust. This suggests that an enhanced signature may be always available for a long range missile - even if it does not burn in the ionosphere.

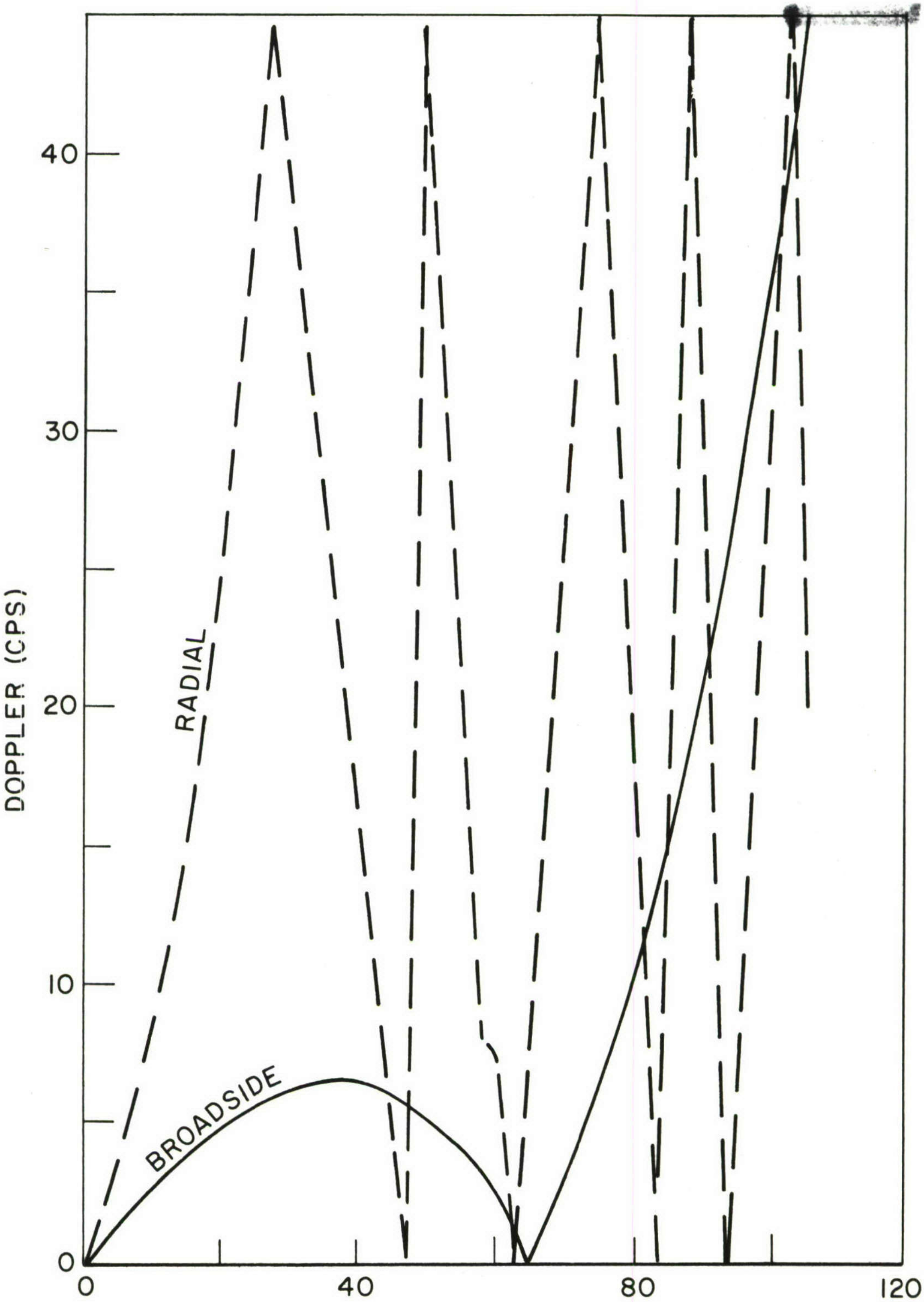


Figure C1 - Near extremes for A-2 Polaris doppler frequency versus time after launch. The dashed curve is for a missile going nominally toward the radar. The solid curve is for a near broadscale but slightly receding launch. Other factors are distance 650 naut. mi., frequency 19 mc, reflecting layer height of 140 km, and repetition rate of 90 pps.

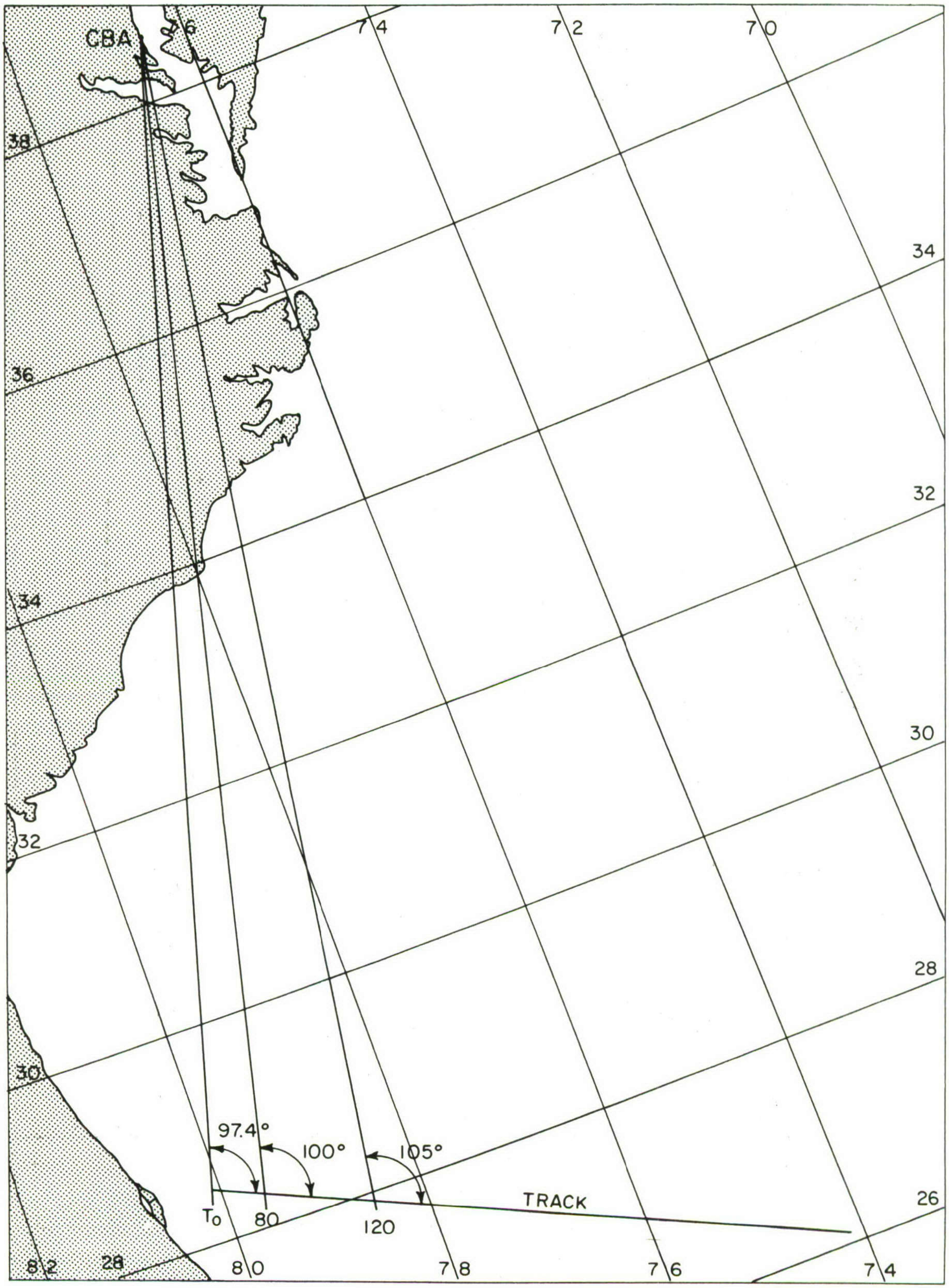


Figure C2 - Plan presentation of missile track and radar view.

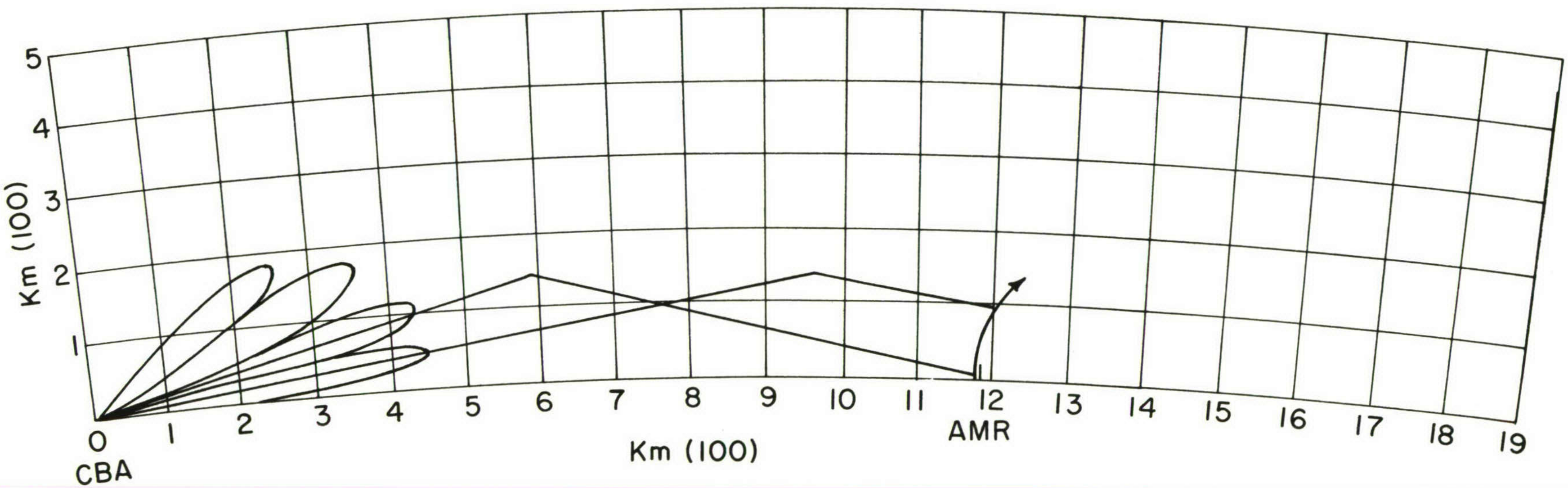
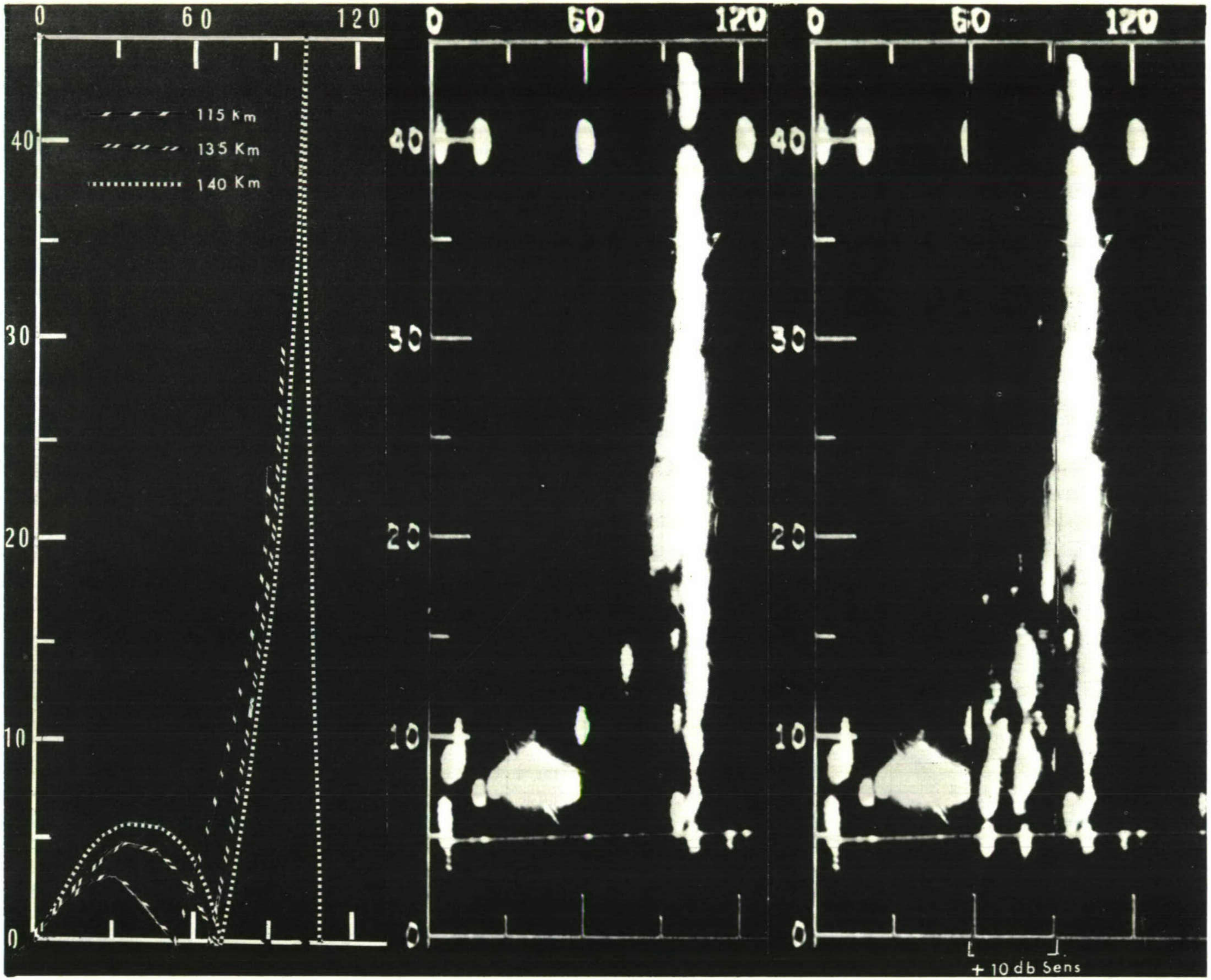


Figure C3 - Illumination geometry in the vertical planes that include both the radar and missile. Antenna lobe pattern with the first loop at 4^{o} and the second at 12^{o} is indicated.

[redacted]



(a) (b) (c)

Figure C4 - (a) Doppler versus time after launch computed for three ionospheric reflecting heights. Doppler given in cps on vertical. Time given in seconds on horizontal. (b) Real time doppler history readout for Test 0238. (c) A later analysis similar to that of Figure C4(b) except that sensitivity was increased by at least 10 db for times between 60 and 90 sec.

[redacted]

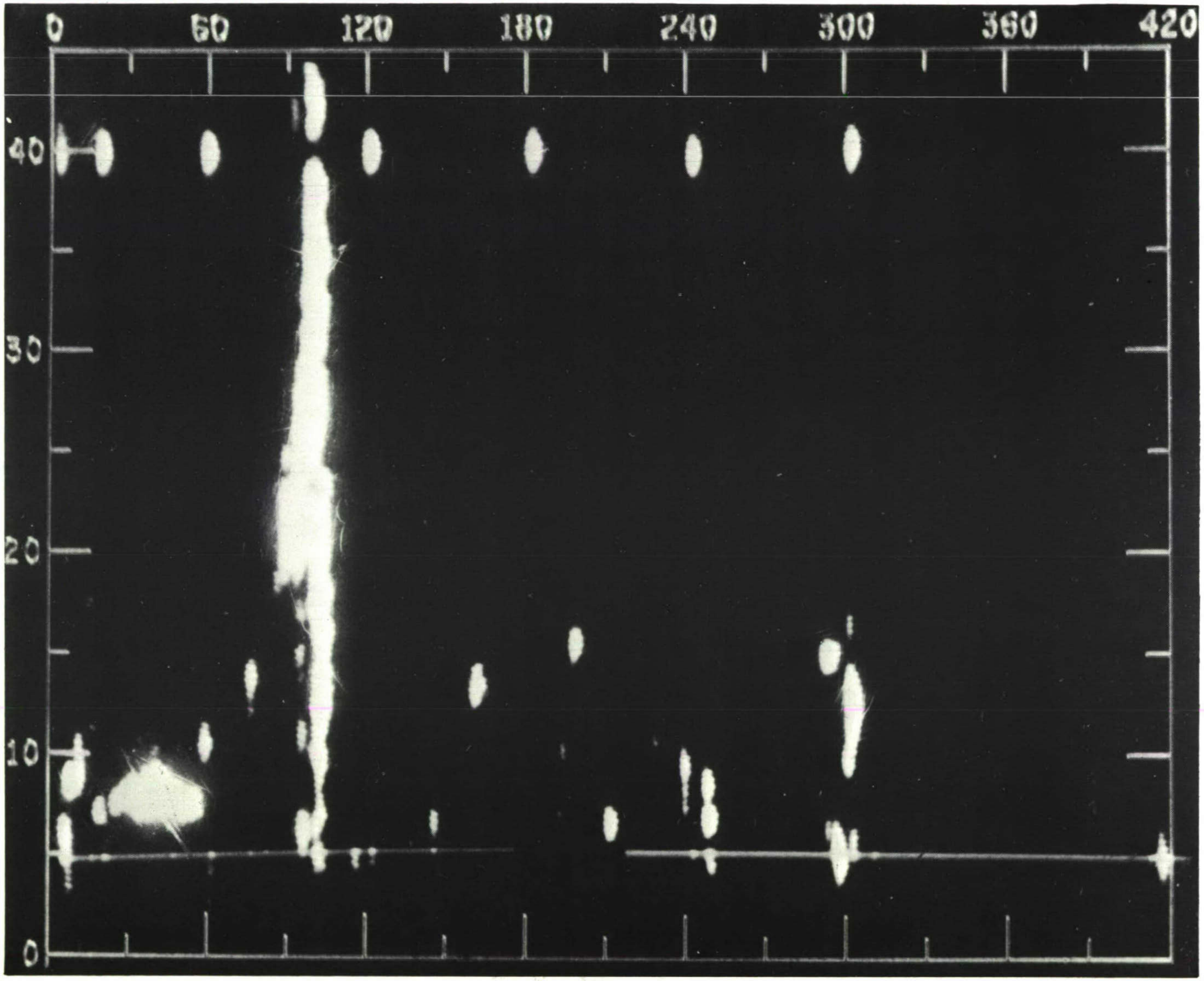


Figure C5 - A picture taken of the Doppler history display 7 minutes after launch. As in Figure C4, doppler in cps is on the vertical; time after launch in seconds is on the horizontal.

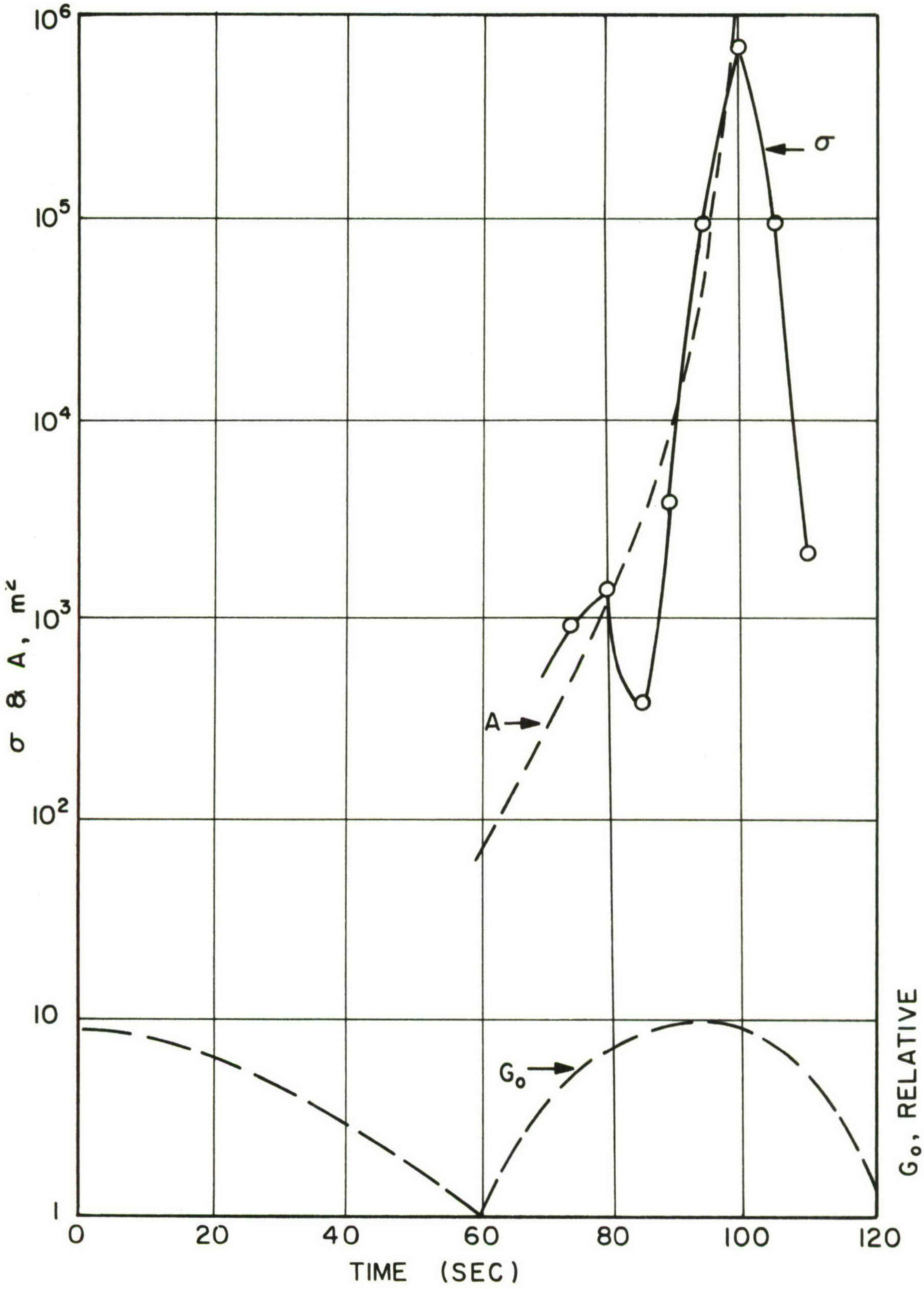


Figure C6 - Radar echoing cross section, α; area of a section through the exhaust cut perpendicular to flow, A; and antenna gain plotted against time after launch.

[redacted] [redacted]

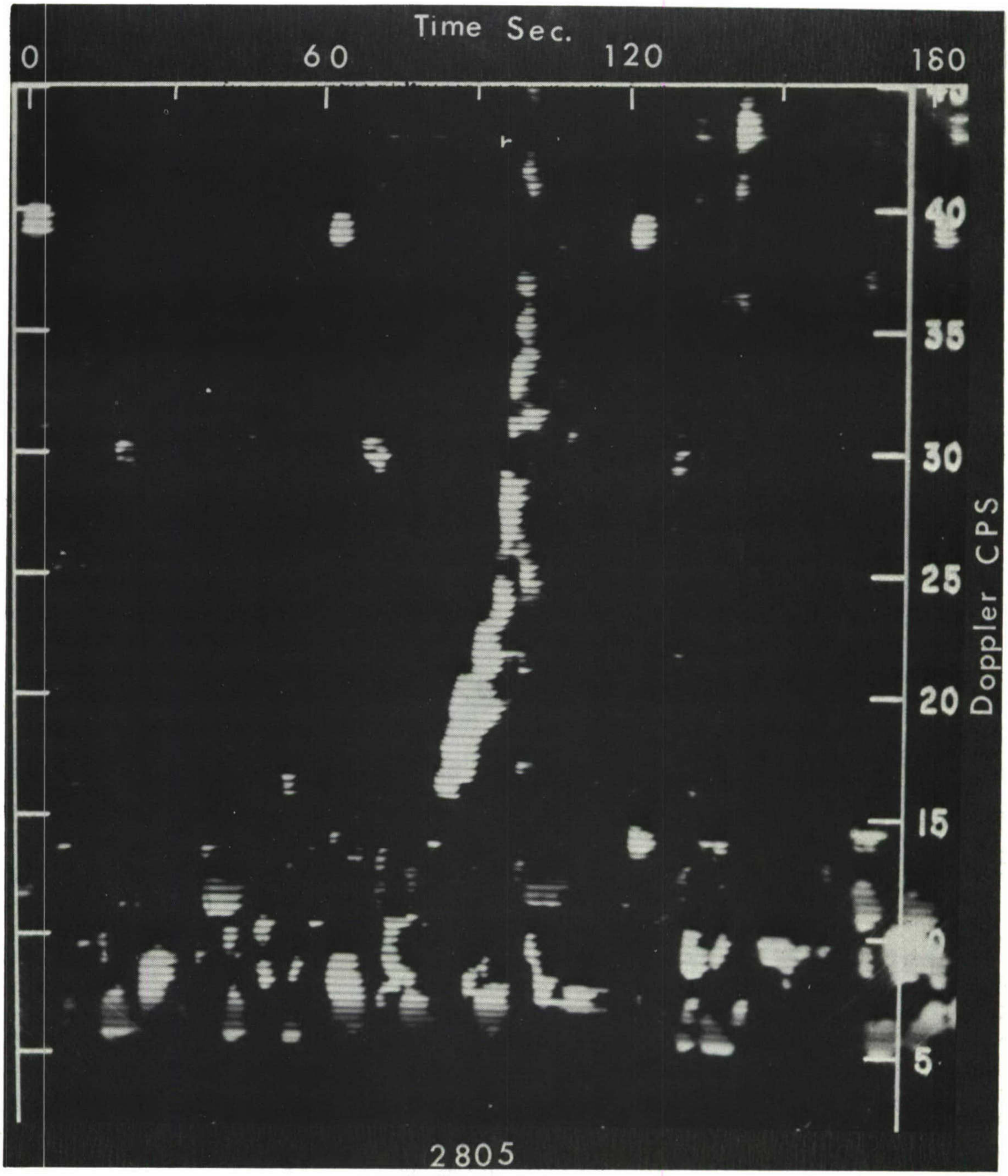


Figure C7 - AMR 2805 range gated doppler history. The radar was on 18 mc. Big echoes start at 80 seconds after lift off at 61 km and an absolute velocity of 7700 fps.

[redacted]

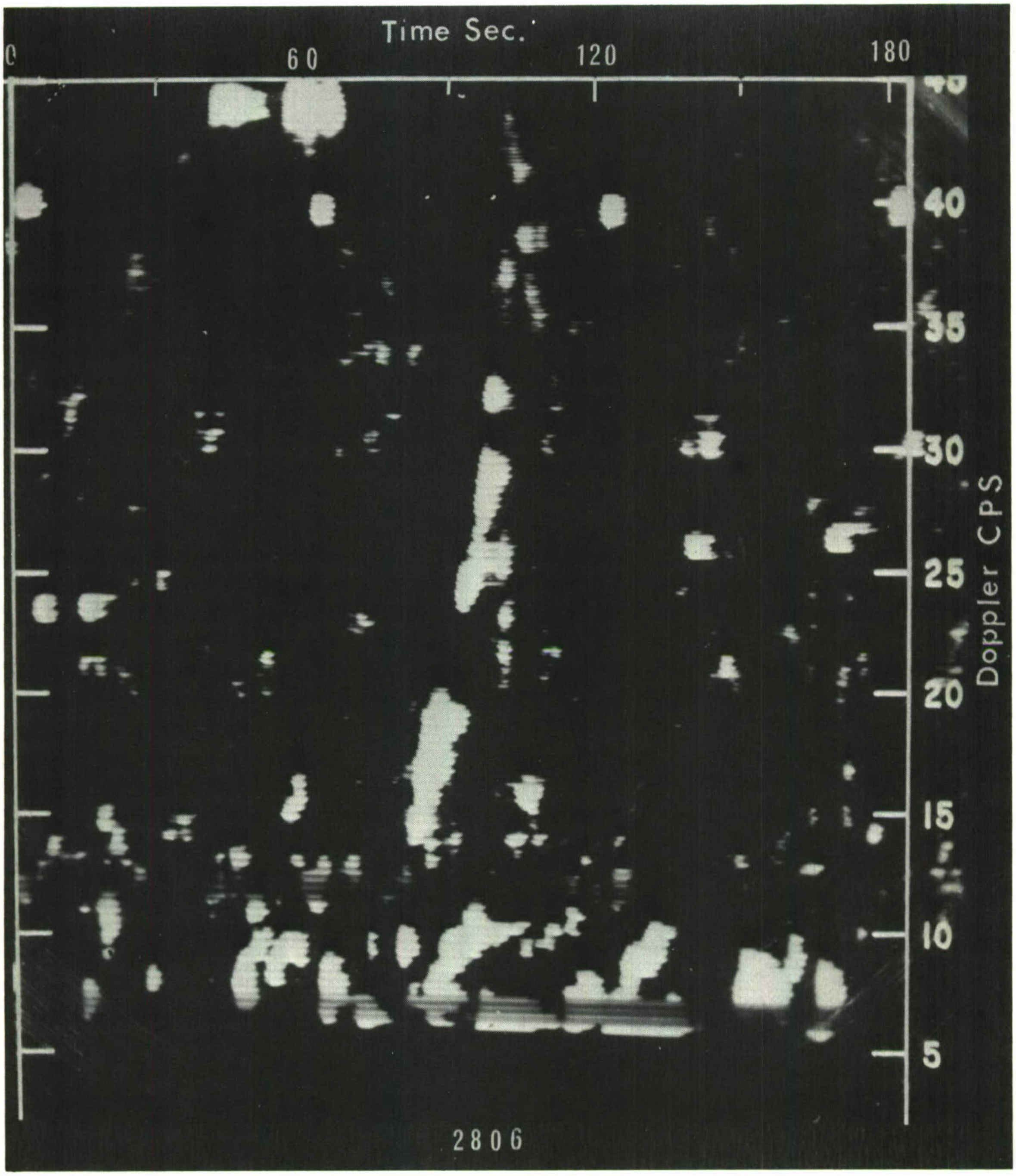


Figure C8 - AMR 2806 range gated doppler history. The radar was on 18 mc. Big echoes start at 82 seconds after lift off. Estimated to be at 61 km and with an absolute velocity of 7000 fps.

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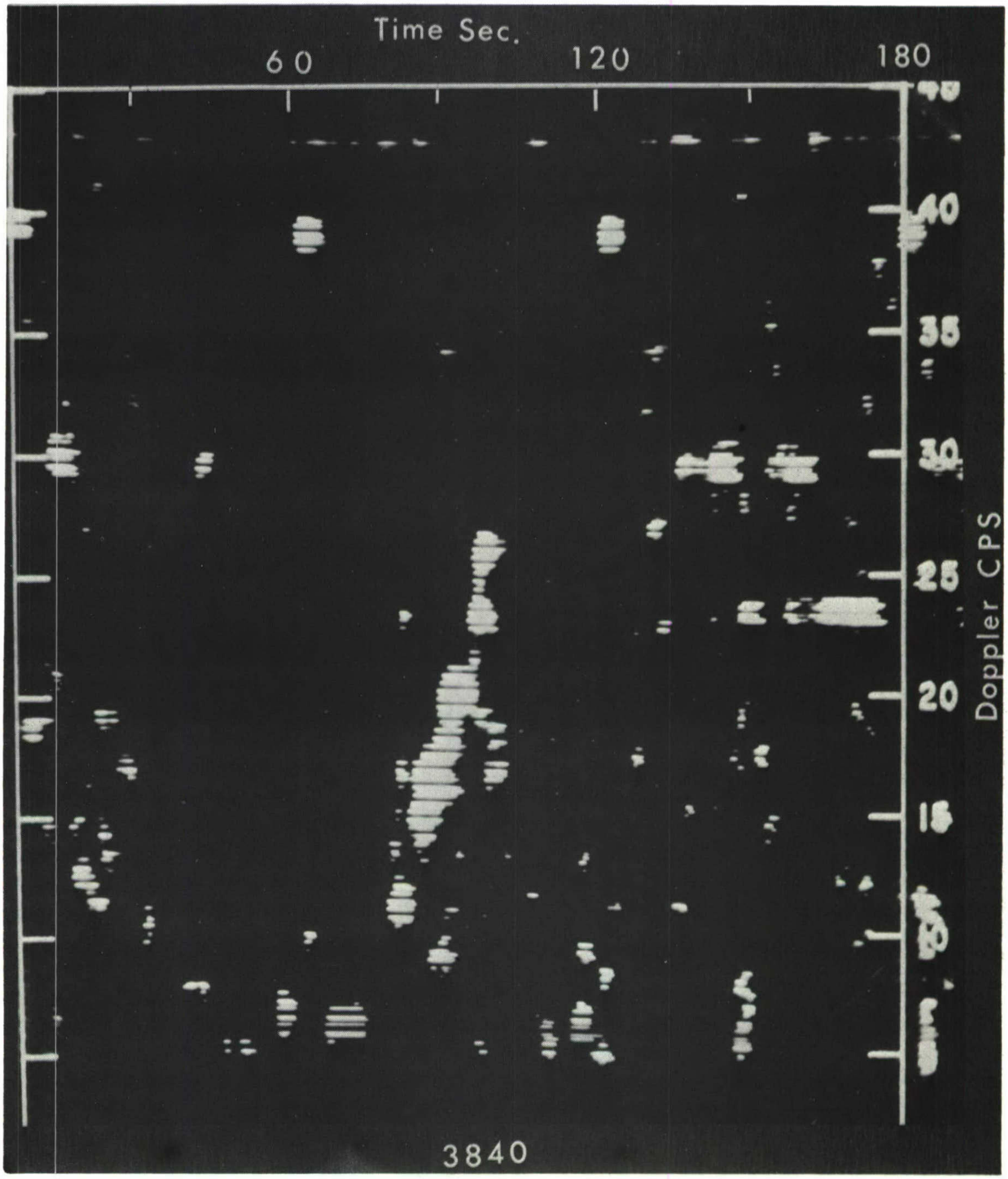

Figure C9 - AMR 3840 range gated doppler history. The frequency was 15.6 mc. Big echoes start at 79 seconds, 60 km and 7500 fps absolute velocity.

[redacted]

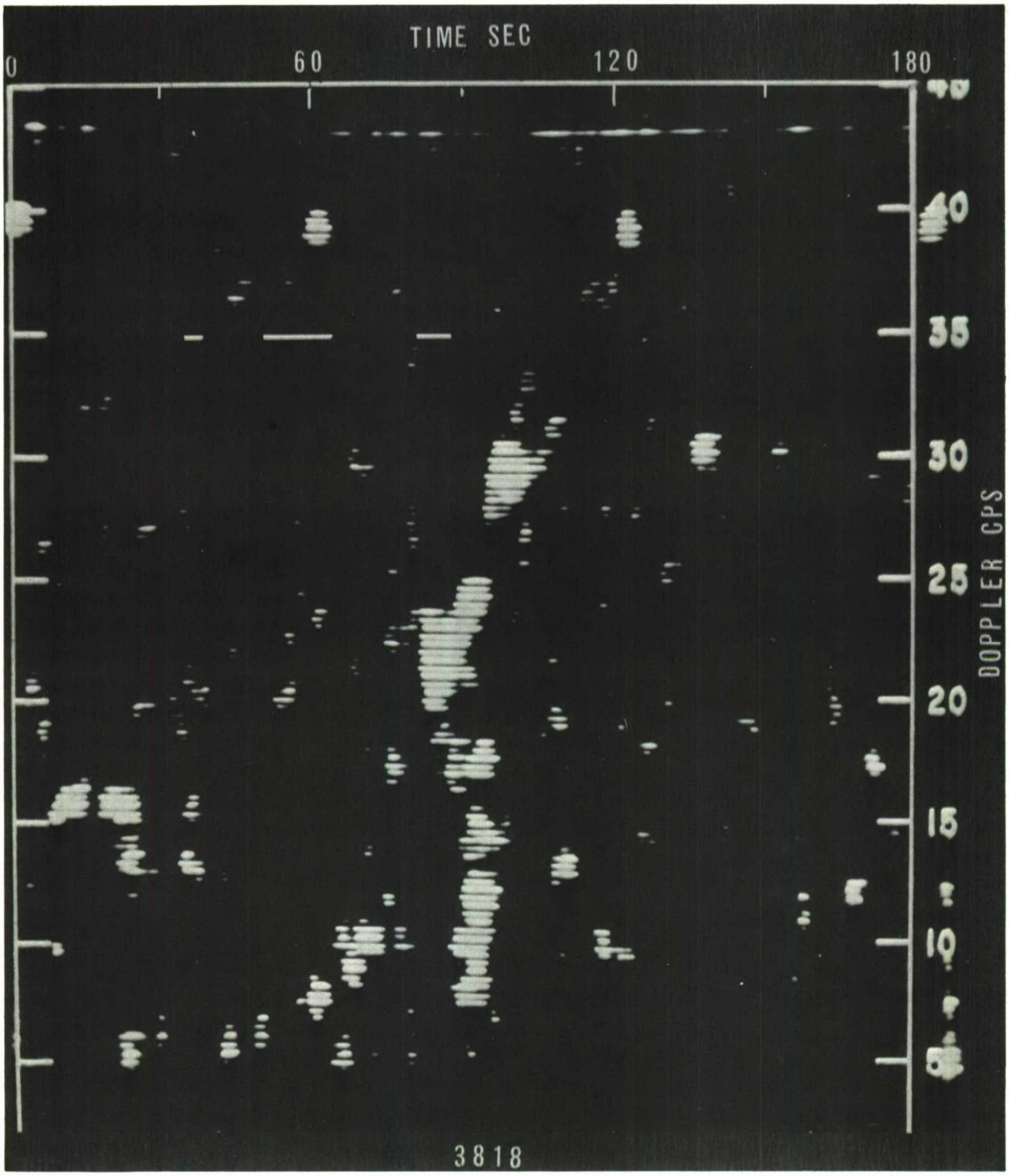

Figure C10 - AMR 3818 range gated doppler history. Big echoes start at 81 seconds, 56 km and 7200 fps absolute velocity.

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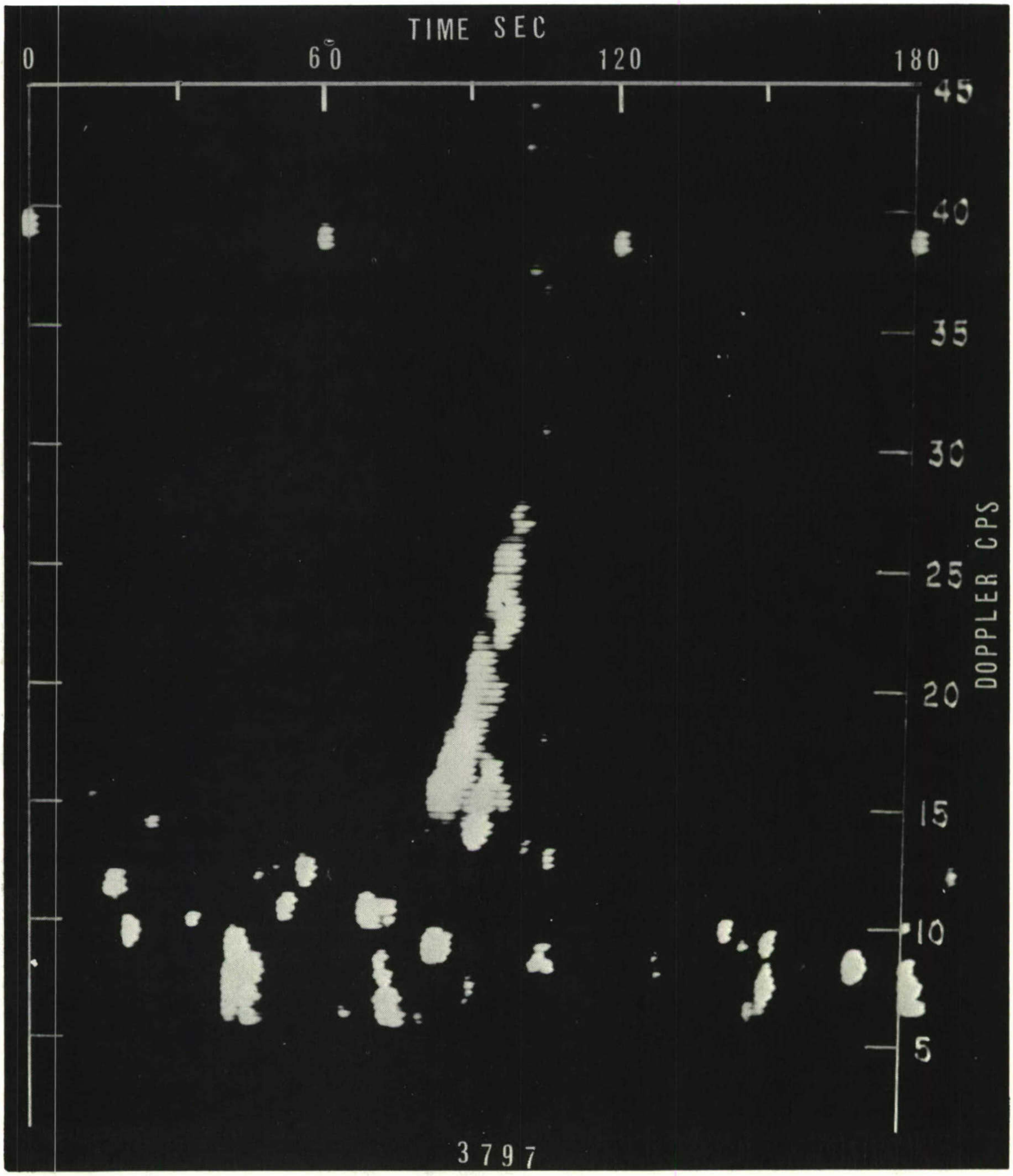

Figure C11 - AMR 3797 Doppler history with 20 naut. mi. range gate centered on 665 naut. mi. Big echoes start at 80 seconds, 56 km and an absolute velocity of 7100.

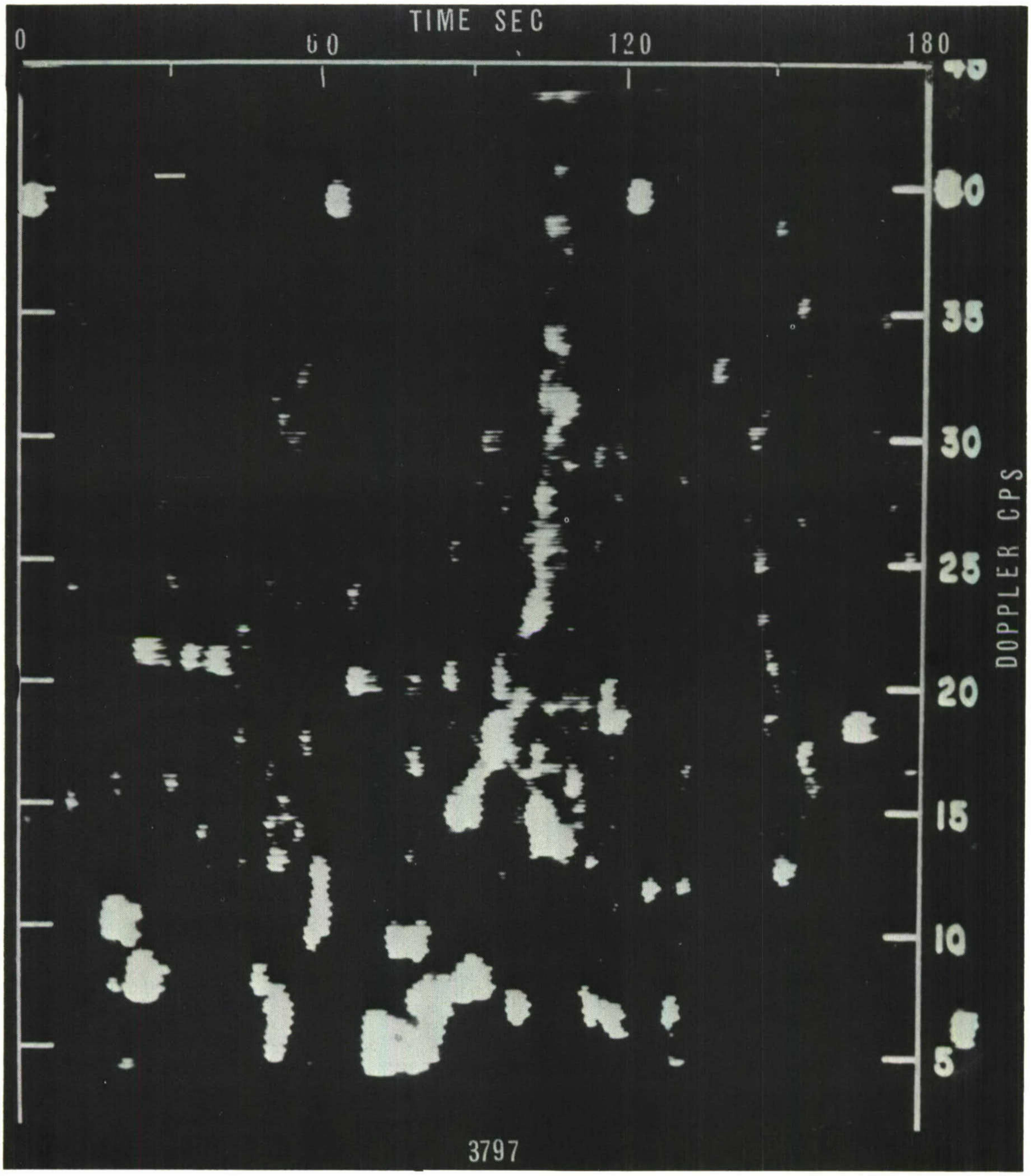

Figure C12 - AMR 3797 Doppler history with a 20 naut. mi. range gate centered on 730 naut. mi. Note the aircraft track that is starting to show at about 20 cps.

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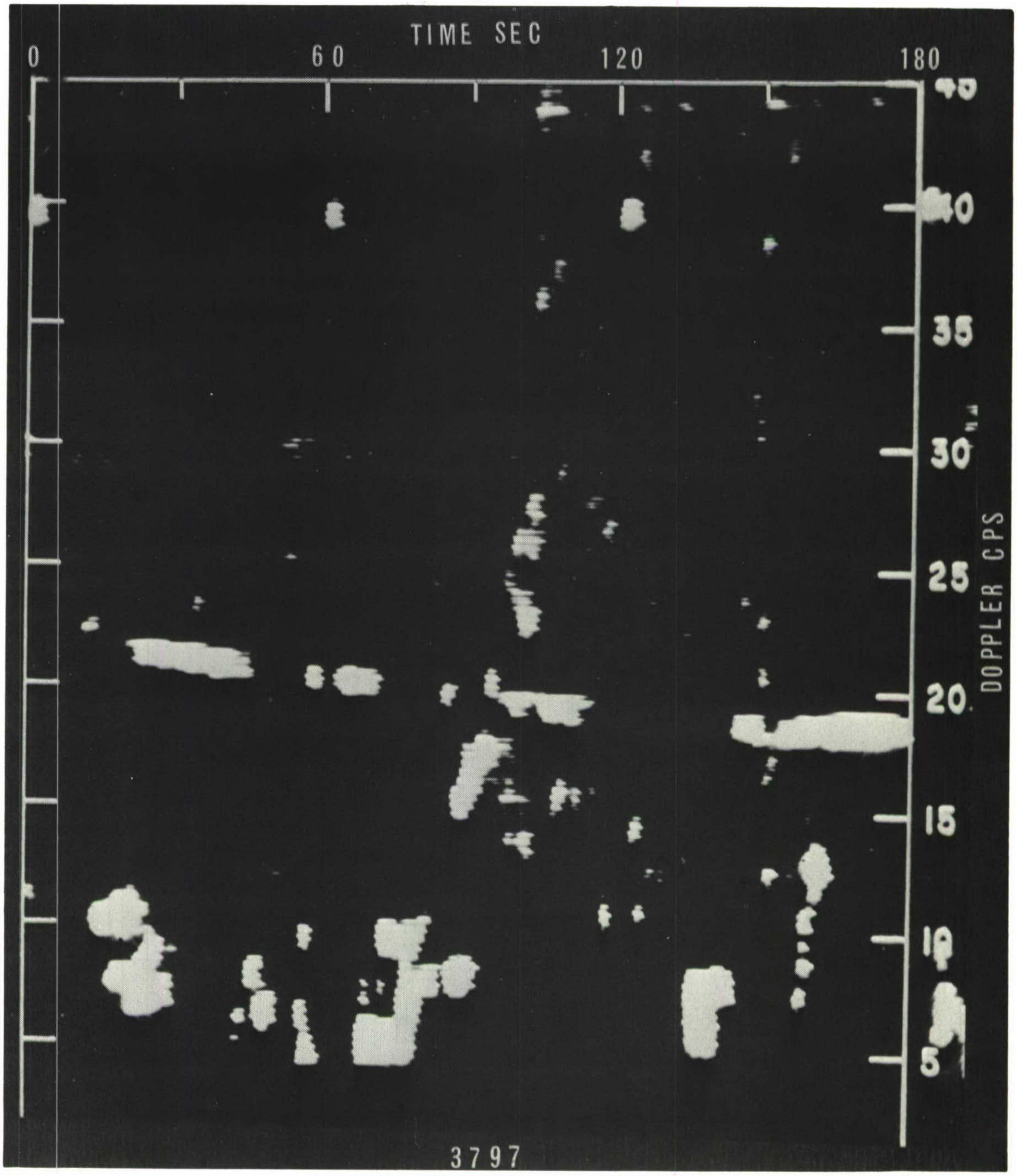

Figure C13 - AMR 3797 Doppler history with a 20 naut. mi. range gate centered on 750 naut. mi. This gate position illustrates an aircraft track at about 20 cps.

[redacted]

APPENDIX D
HF RADAR DETECTION OF EXHAUST ECHOES AND PROMPT PERTURBATIONS

J.L. Ahearn, J.M. Headrick and F.H. Utley
U.S. Naval Research Laboratory
Washington, D. C.

I. INTRODUCTION

The early low power, MADRE HF radar system located at NRL was used to view missile signatures as the missile passed through the ionosphere. This system employed a narrow band technique which gave doppler versus range information. The transmitter radiated shaped pulses of 40-kw peak power and 2-kw average at 180 prf. At that time, frequency of operation was limited to 26.6 Mc. Even with this operating power and frequency limitation good results were obtained on a number of Atlantic Missile Range launches. These results were reported in a series of NRL (limited distribution) letter reports. Atlas and Titan launches provided good signatures because their engines burn high in the ionosphere. At this time it is perhaps appropriate to present data taken during a recent AMR Titan II launch for comparison with that obtained on an early Titan launch. The main difference between these two tests is the operating transmitter power - 40-kw peak compared to our present 4.6-megawatt peak.

II. EXPERIMENTAL RESULTS

Figure 1 shows a series of real time MADRE primary analysis displays taken from a letter report dated 22 March 1961. This test was AMR 1007, launch time was 10:19:37 A.M. EST 29 Sep 1960. The operating frequency was 26.6 Mc. The earth backscatter extended from 2400 to 3800 km and from 4700 to 6700 km. Time after launch in minutes and seconds appears on each frame. The ordinate shows doppler frequency from 0-90 cps. The abscissa shows range from 0-450 naut. mi. Range intervals beyond 450 naut. mi. are superimposed on the first interval.

The first missile effect occurs at T_o + 288 sec at a probable range of 1400 naut. mi. This is a prompt perturbation type with the exhaust acting as a refractor. The next large effect appears at T_o + 308 at a probable range of 1200 naut. mi. This is another prompt perturbation signature; on the same frame a faint exhaust boundary reflection appears at a range of 800 naut. mi. via a refracted ionospheric ray path. Ranges are given as probable because the unambiguous range interval is 0-450 naut. mi.

As time went on, NRL efforts were directed toward missile detections earlier in time. This meant placing energy near the launch site which is not an optimum situation for observing the missile associated effects occuring later in time as the missile travels through the ionosphere.

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On a recent Titan II launch it was decided to view the effects in a manner similar to that for the early AMR Test 1007. This Titan II launch was AMR Test 0158 and was viewed by the NRL coherent pulse doppler radar located on Chesapeake Bay, 642 naut. mi. from the launch area at Cape Kennedy. This radar is an improved higher power version of the original MADRE located at NRL, Washington, D.C. The Titan II was launched at 4:09:50 P.M. EST on 9 April 1964. The HF radar was operated on 15.595 Mc at a 60 prf with 4.6-megawatts peak power and 100-kw average. The unambiguous radar range extended from 0-1350 naut. mi. During this test the closest backscatter was about 900 naut. mi. Therefore, targets appearing beyond line of sight in the first 0-450 naut. mi. range interval probably come from the 1350-1800 naut. mi. range. Thus, a given prf coupled with knowledge of the closest backscatter range gives in this case a pseudo 0-1800 naut. mi. unambiguous radar range. Of course the first doppler fold occurs at 30 cps.

Figure 2 shows the backscatter situation at 4:15 P.M. EST with the radar antenna pointed at a bearing of 189°. The calibration signals which appear on this same figure correspond to a 1 millivolt peak-to-peak signal at the antenna terminals. The largest backscatter signal is about 4 mv peak to peak at a range of 1050 naut. mi. Figure 3 is a sketch of the illumination geometry for this test based on the backscatter situation and ionograms from the NBS station at Ft. Belvoir, Va. and a sounding station at Cape Kennedy. The backscatter returns came via both single and double hop. Figure 4 shows the probable signal reflection and perturbation paths. The paths are numbered in the same order as the signatures occur in time. A direct exhaust boundary reflection travels via path 1. This is a low level signal observable at about T_o + 170 seconds but only on a processing channel which has about 60-db backscatter rejection filtering. Path 2 carries a perturbation signature which is called a prompt perturbation and occurs T_o + 175 sec. Here the missile exhaust refracts energy back to the ground. The exhaust acts like a patch of perturbed ionosphere. Path 3 is an F_1 refracted exhaust boundary reflection which occurs at T_o + 188 sec. Path 4 is another prompt perturbation occurring at T_o + 203 sec at a range of 1050 naut. mi. Path 5 carries the normal backscatter perturbation due to the missile burning in the F-region. These perturbations persist after engine cutoff.

Figures 5a - 5e are composite pictures of the doppler vs range display for the stated time in seconds after missile launch. The position of the calibration signal is noted in the first strip. The data for these figures was gathered in 450 naut. mi. range blocks and then the composite picture taken. This data was processed with only 30-db backscatter signal rejection. Thus signatures via paths 2, 3, 4 and 5 appear. Figure 6 shows the direct reflection via path 1. Here 60-db backscatter rejection was used. Naturally all signals which appear on these doppler vs range displays have doppler frequencies outside the comb type notches in the backscatter rejection filters.

[redacted]

Figure 7 shows the apparent radar cross section of the exhaust boundary reflection via path 3. This occurs at a slant range of 700 naut. mi. The maximum signal received during either the indicated 5 or 10 second time interval is used in determining the cross section.

III. CONCLUSION

The missile signatures reported in this paper depend on the manner in which the missile track is illuminated and on whether the missile engines are burning in the ionosphere. The signatures can generally be distinguished from natural phenomena. The prompt perturbation effects may not easily be distinguished from the exhaust boundary reflections. Using all the effects aids one considerably in obtaining adequate coverage.

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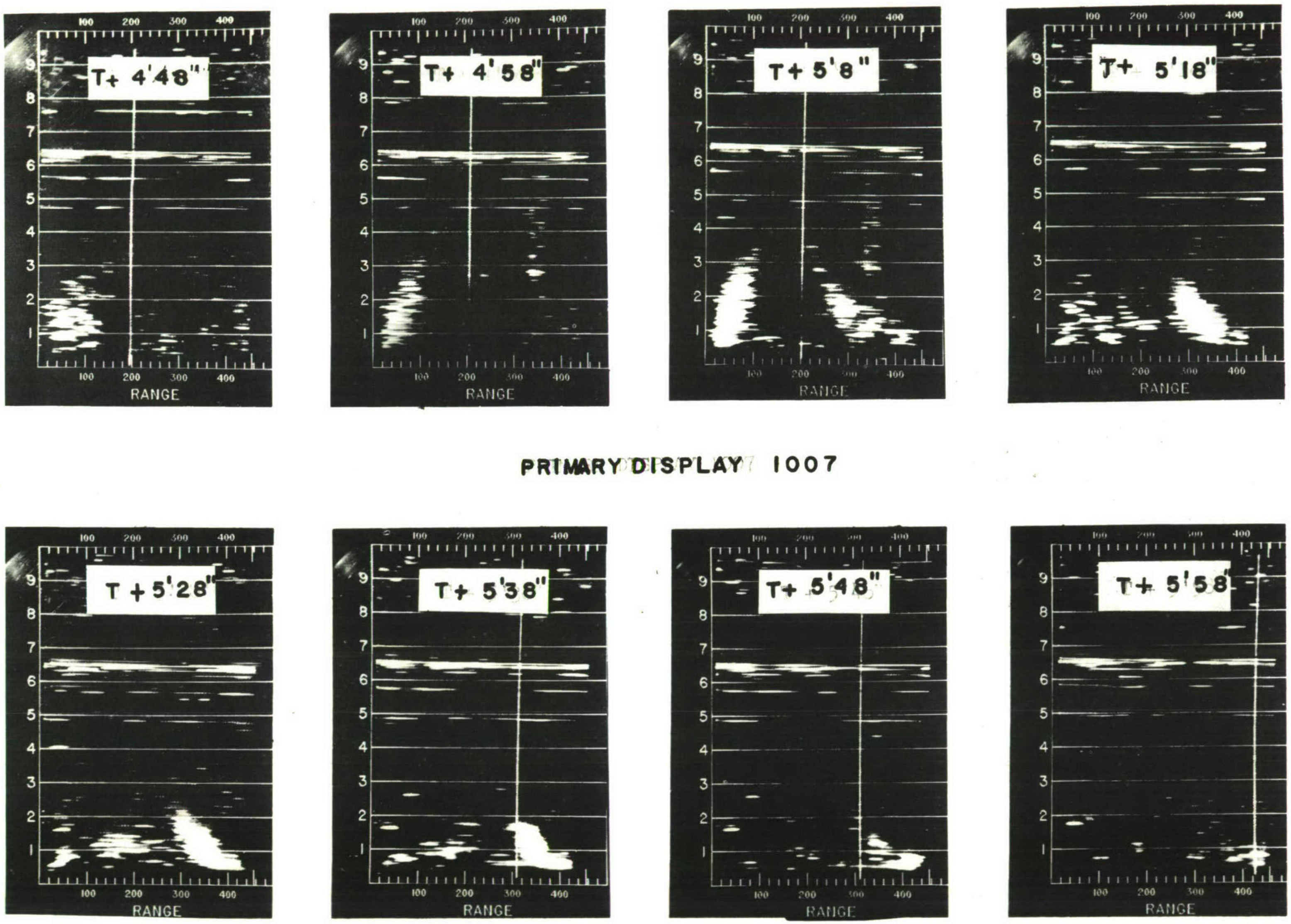

Figure D1 - Doppler range display for AMR test 1007

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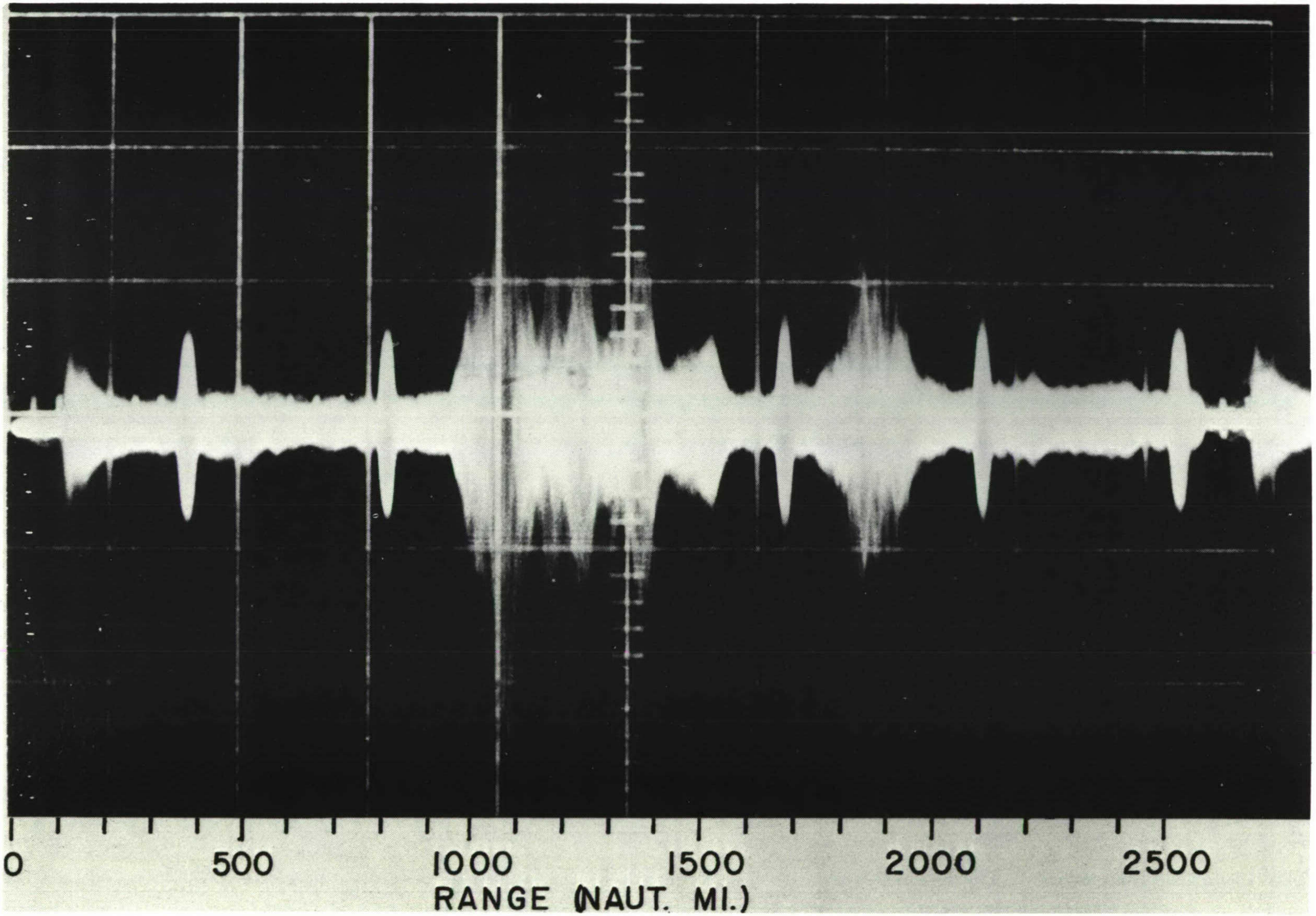

Figure D2 - Backscatter at a bearing of 189°

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[redacted]

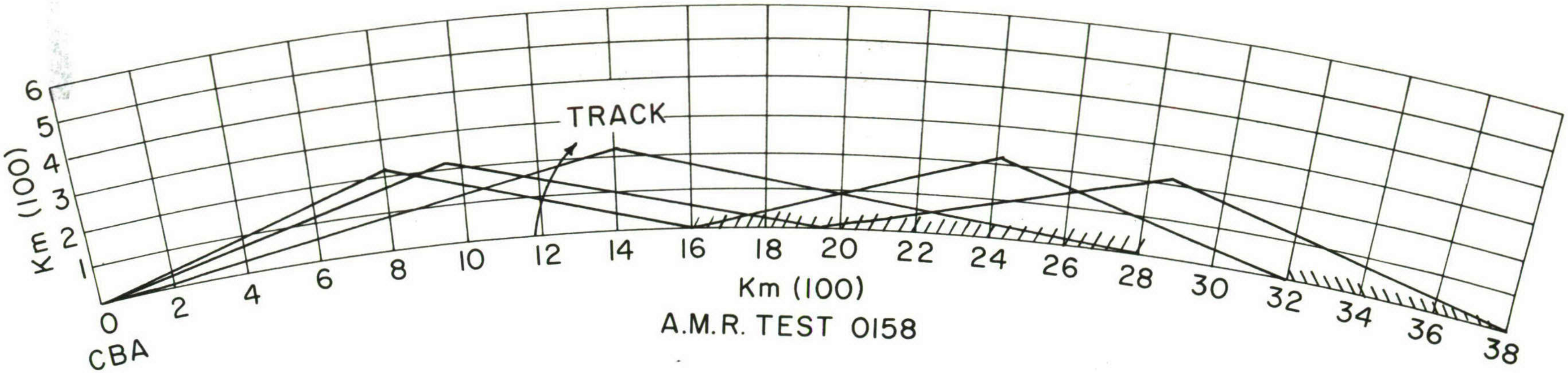

Figure D3 - Illumination geometry

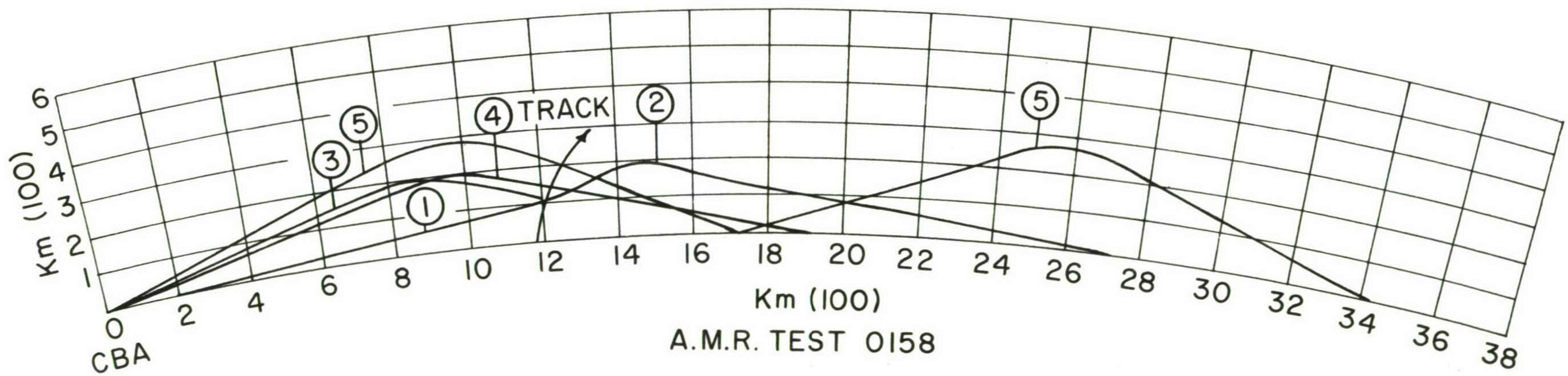

Figure D4 - Probable reflection and perturbation signal paths

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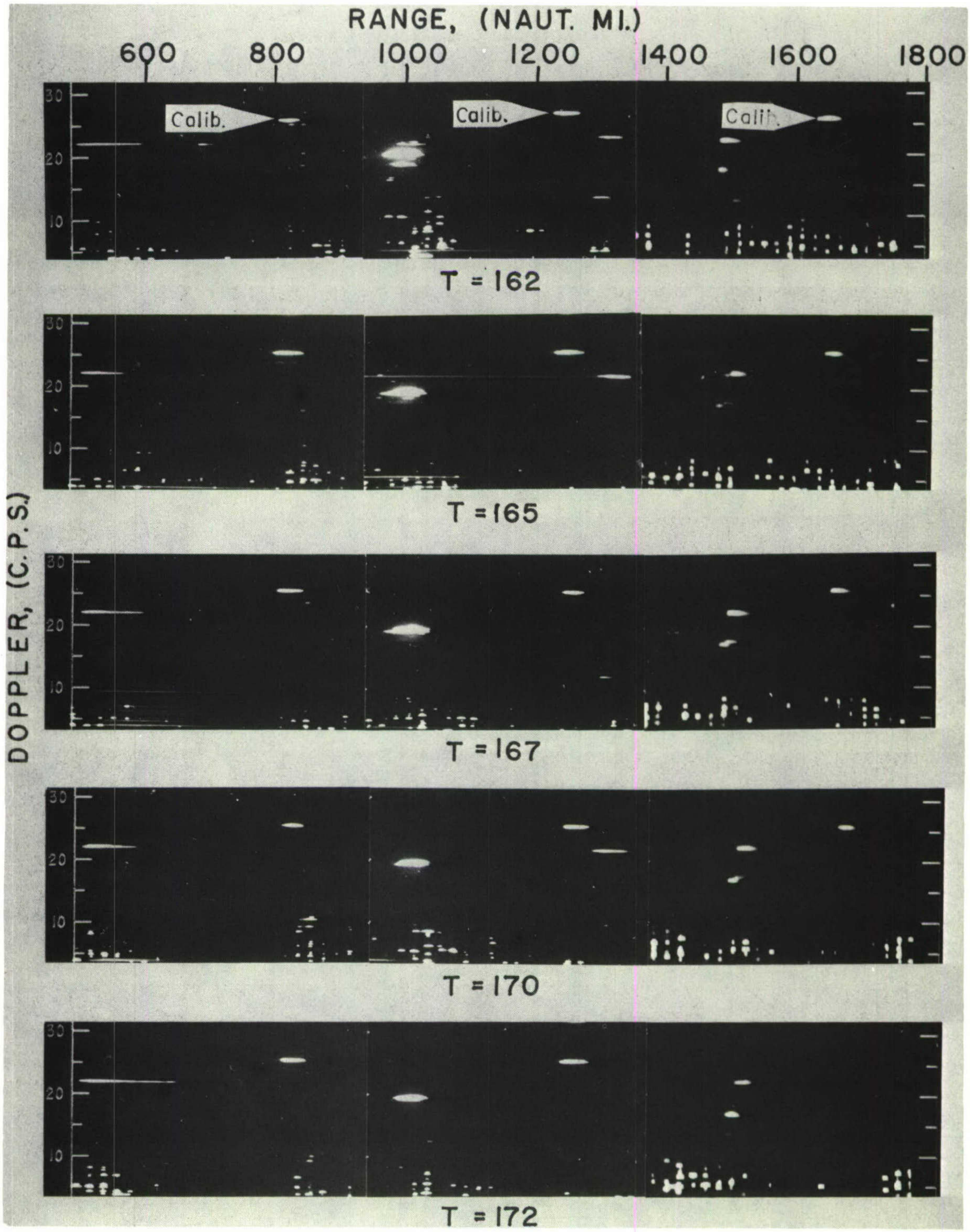

Figure D5a - Missile signatures for test 0158

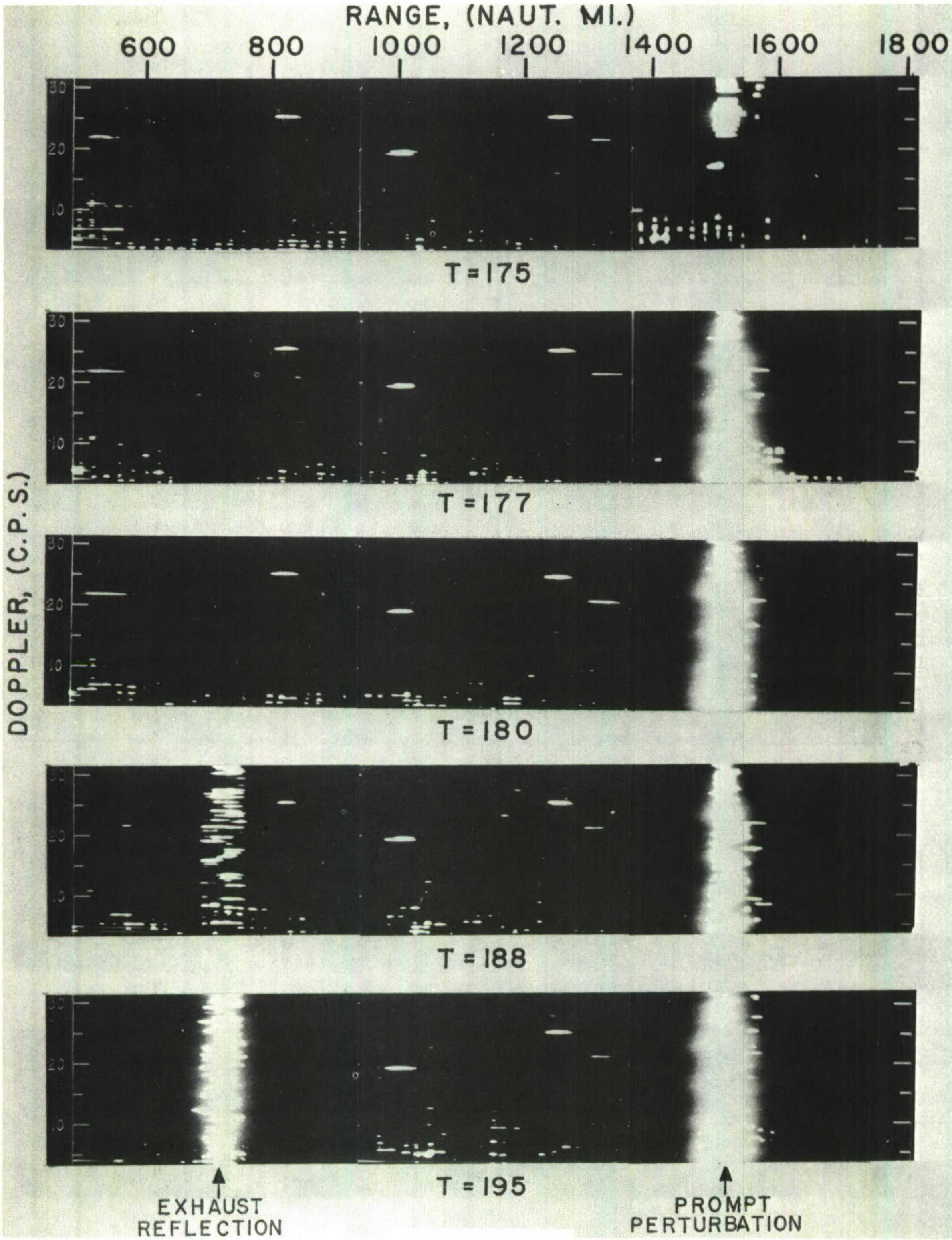

Figure D5b (Continued) - Missile signatures for test 0158

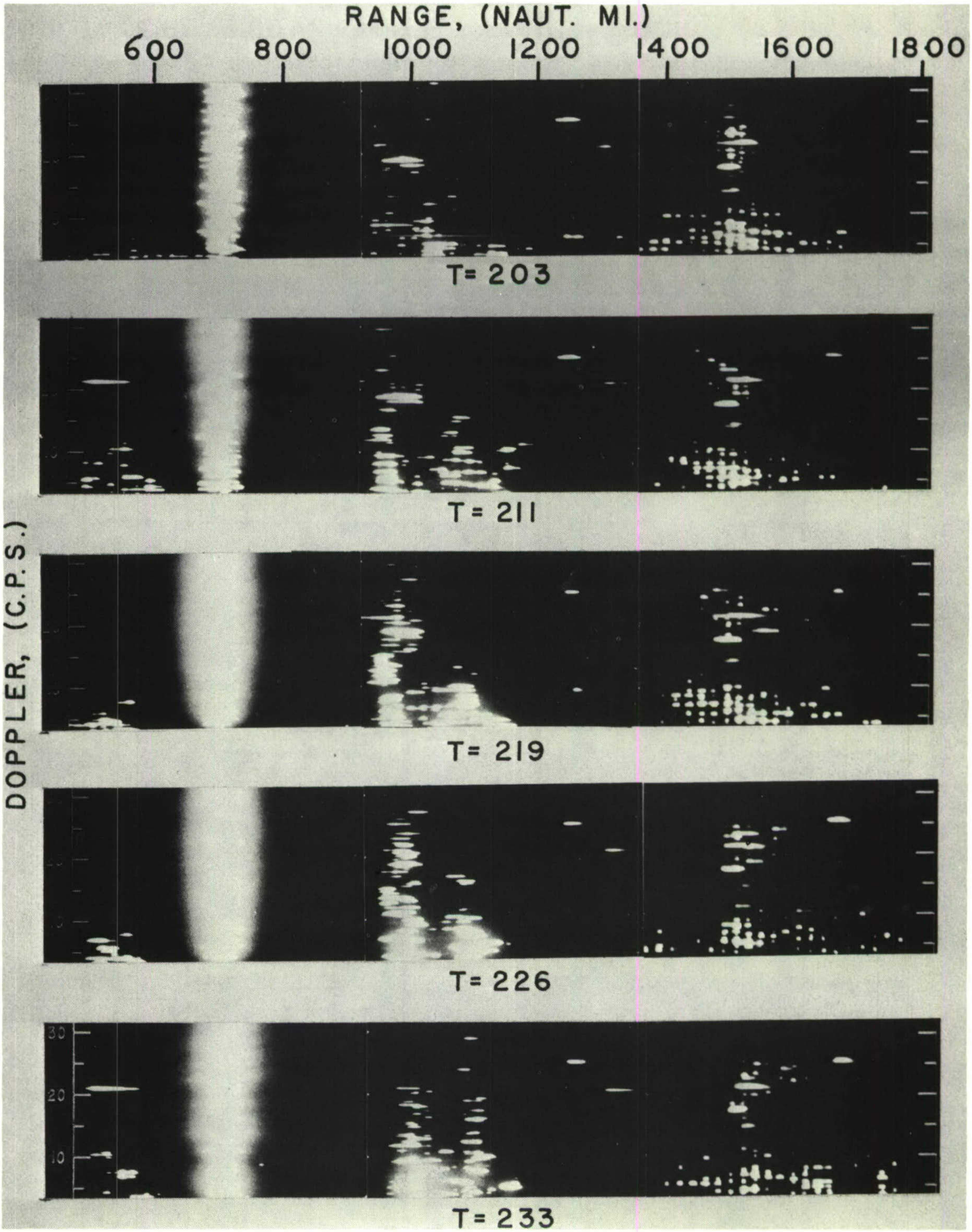

Figure D5c (Continued) - Missile signatures for test 0158

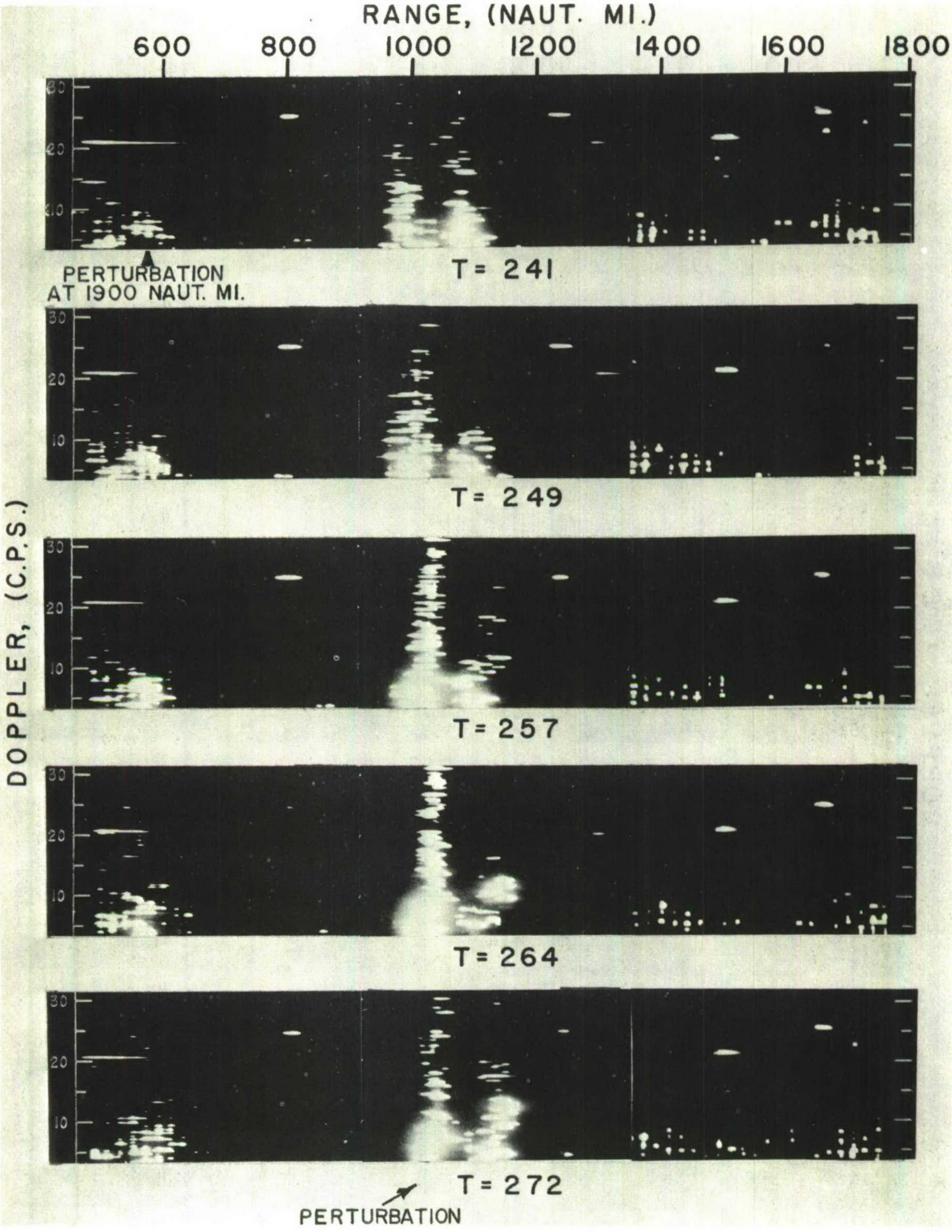

Figure D5d (Continued) - Missile signatures for test 0158

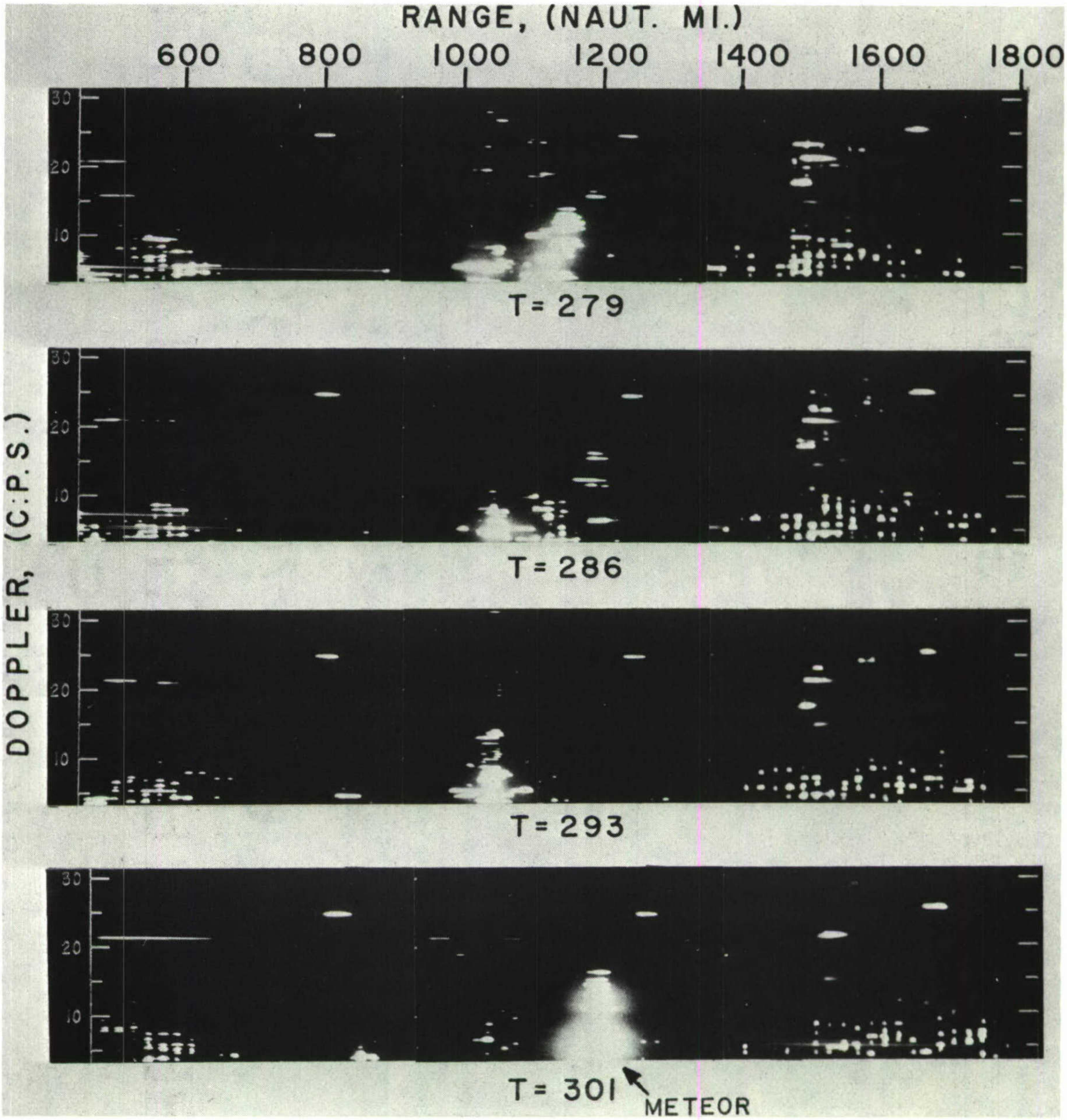

Figure D5e (Continued) - Missile signatures for test 0158

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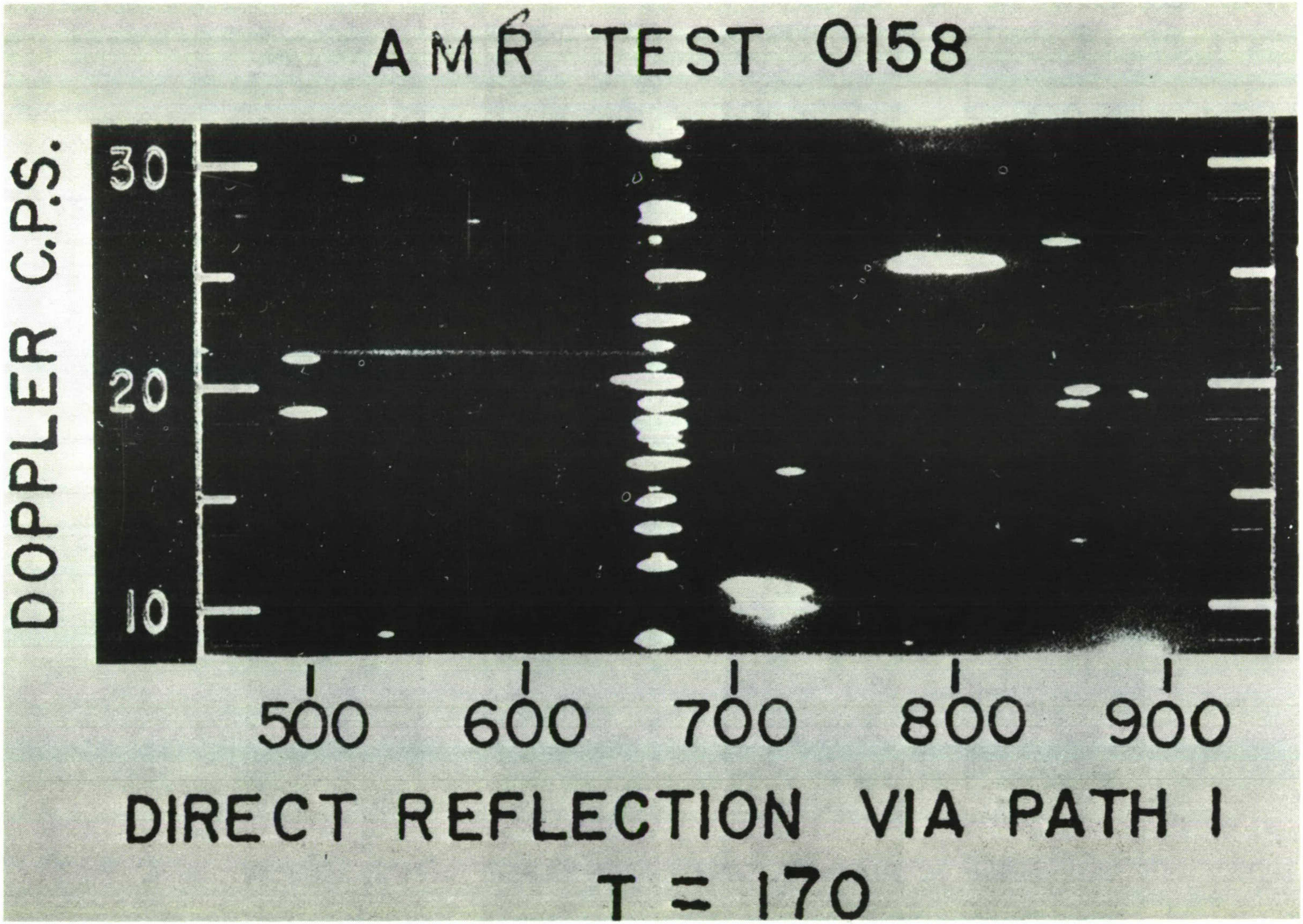

Figure D6 - Direct reflection via path 1.

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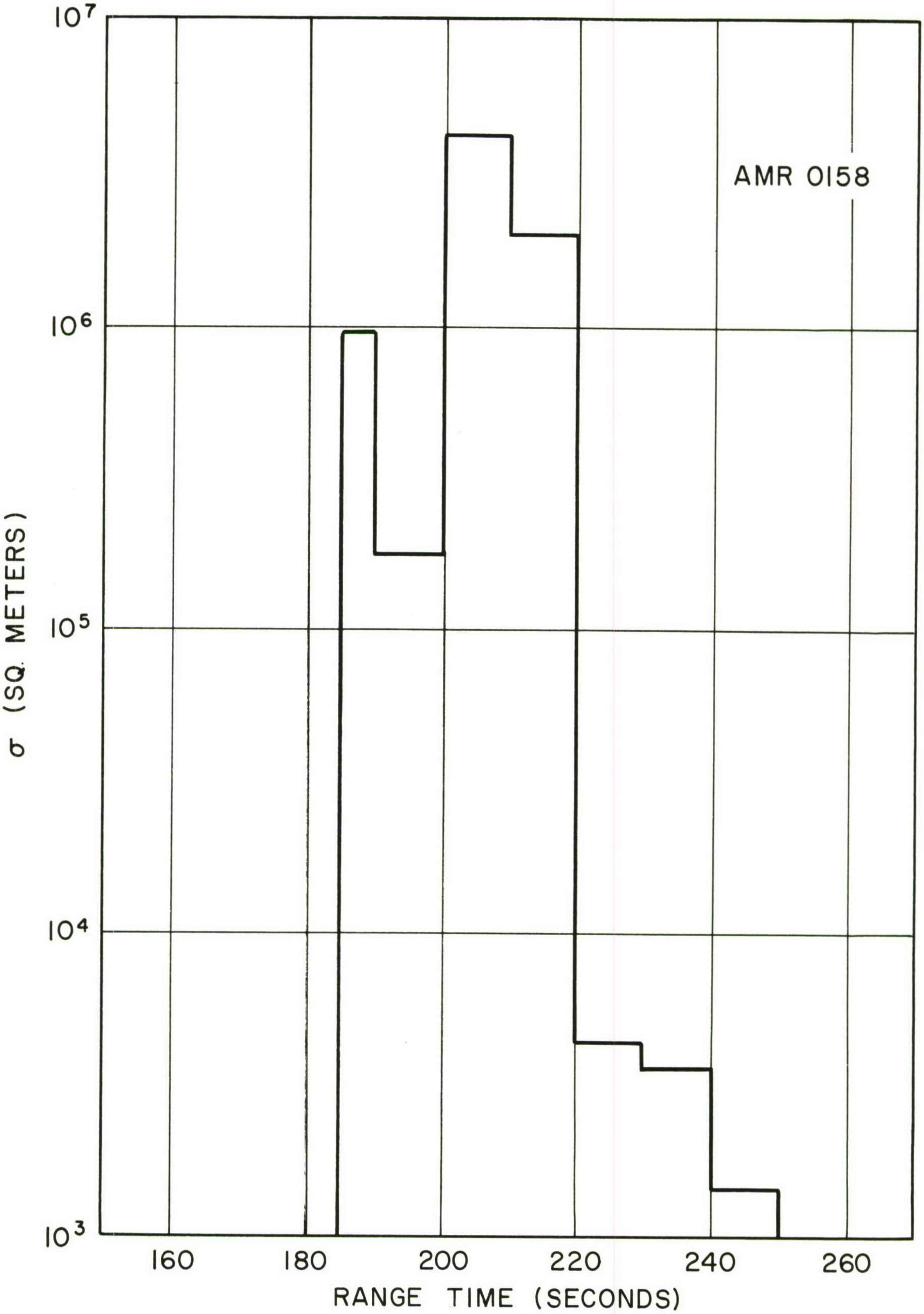

Figure D7 - Exhaust boundary cross section